HANDLING QUALITIES EVALUATION OF A SUPERSONIC TAILLESS AIR VEHICLE

THESIS

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Wright-Patterson Air Force Base, Ohio

AFIT/GAE/ENY/08-M25

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THESIS

Presented to the Faculty

Department of Aeronautics and Astronautics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Aeronautical Engineering

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March 2008

AFIT/GAE/ENY/08-M25

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AFIT/GAE/ENY/08-M25

Abstract

This thesis presents the results of a handling qualities evaluation of a supersonic tailless air vehicle. The 2006 Quadrennial Defense Review mandated the need for the next generation of long-range strike aircraft by 2018. Due to speed and stealth requirements, this resulted in a tailless aircraft with an instantaneous center of rotation located well forward of that of a conventional aircraft. This thesis examines how this center of rotation affected pilot handling qualities ratings. This effect should have been the most pronounced during approach and landing, and was where the testing focused. The goal of this research was to develop a systematic procedure for evaluating the handling qualities of this aircraft, and to determine how different pilot flying techniques or pilot-inceptor interactions influenced them. This procedure was demonstrated in simulator testing and in flight testing on the Calspan-operated Total In-Flight Simulator aircraft.

Acknowledgements

I would first off like to thank God for providing me the inspiration, knowledge, and perseverance to complete this thesis over the past two years. Thank you to my wife for the tremendous and unyielding support while at AFIT and Test Pilot School, you are a truly amazing wife and mother. Thank you also to my son for keeping me smiling on all of our adventures, dream big. This thesis would also not have been possible without the direction of my advisor, Major Paul Blue. Thank you for the ideas and guidance over the past two years. Amy Linklater, Jay Kemper, Curt Clark, Jeff Slutz, and Gary Hellmann all ensured that testing in the Infinity Cube and LAMARS set the highest standard for efficient, well-run simulator testing. A big thanks to all of the folks at AFRL, I hope that the relationship with AFIT continues to grow. Thank you to Paul Germain at Northrop Grumman for all of your work with STAV. The Calspan pilots, engineers, and maintainers involved with TIFS testing were absolutely fantastic. Thank you to Paul Deppe for your leadership and experience during flight testing. Thank you to our TMP staff advisor Bill Gray, whose influence helped to expand the scope of this research. Finally, huge thanks to the rest of the HAVE STAV test team: Nate Cook, Matt Domsalla, Brian Neff, Jason Porter, and Bill Quashnock. Thank you all for the work you put into my little side project at TPS. It’s only fitting that STAV worked our tails off on our half-way tour around the world.

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List of Symbols

Symbol – Definition

α – angle of attack of an aircraft

β – angle of sideslip of an aircraft

γ – flight path angle of an aircraft

δ – representation of the partial derivative of a function

ϕ – roll angle of an aircraft

θ – pitch angle of an aircraft

ψ – yaw angle of an aircraft

ω_{sp} – short period frequency

n – load factor of an aircraft

ζ_p – phugoid damping ratio

ζ_{sp} – short period damping ratio

$T_{\theta 2}$ – time to double amplitude

$C_{m\alpha}$ – pitch stability (pitching moment coefficient due to angle of attack)

$C_{l\beta}$ – dihedral effect (roll moment coefficient due to sideslip)

$C_{n\beta}$ – directional stability (yaw moment coefficient due to sideslip)

List of Abbreviations

AFB – Air Force Base

AFIT – Air Force Institute of Technology

AFRL – Air Force Research Laboratory

AGL – Above Ground Level

ASTTA – Avionics Systems Test and Training Aircraft

CAP – Control Anticipation Parameter

CG – Center of Gravity

CHR – Cooper-Harper Rating

DFLCS – Digital Flight Control System

DI – Dynamic Inversion

DoD – Department of Defense

FQ – Flying Qualities

GPS – Global Positioning System

HQ – Handling Qualities

HUD – Heads Up Display

ICR – Instantaneous Center of Rotation

ICS – Infinity Cube Simulator

ILS – Instrument Landing System

KIAS – Knots Indicated Airspeed

LAMARS – Large Amplitude Multi-mode Aerospace Research Simulator

LRS – Long Range Strike

NASA – National Aeronautics and Space Administration

NGC – Northrop Grumman Corporation

PIO – Pilot In-the-Loop Oscillation

PTI – Programmed Test Input

QDR – Quadrennial Defense Review

STAV – Supersonic Tailless Air Vehicle

TIFS – Total In-Flight Simulator

TMP – Test Management Project

TPS – Test Pilot School

US – United States

USAF – United States Air Force

VISTA – Variable-Stability In-Flight Simulator Test Aircraft

VSS – Variable Stability System

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HANDLING QUALITIES EVALUATION OF A SUPERSONIC TAILLESS AIR VEHICLE

1.0 Introduction

1.1 Purpose

Since the dawn of heavier-than-air flight just over a century ago, man has attempted to qualify and quantify his experience in the air. What began as discussion between the two Wright brothers on how to improve their flying machine developed into the methods used by modern test pilots to describe a new aircraft. As the United States Air Force modernizes during the first part of the 21st century, it will continue to test and evaluate new concept aircraft to determine which will best satisfy mission requirements. The handling qualities evaluation is part of this test and evaluation process. In simple terms, handling qualities describe the characteristics or dynamics of both the pilot and aircraft working together. The better the handling qualities (HQ) of an aircraft, the more likely a pilot will be able to accomplish the design mission. The purpose of this thesis was to conduct a handling qualities evaluation of a new concept aircraft proposed for the next generation bomber: a supersonic tailless air vehicle (STAV). In addition, it sought to determine if different pilot flying characteristics or pilot-inceptor interactions impacted the pilot's opinion of the aircraft handling qualities.

1.2 Motivation

Every four years, the US Department of Defense (DoD) conducts a Quadrennial Defense Review (QDR) of its vision and mission. The 2006 QDR outlined plans for a new USAF (United States Air Force) long-range strike aircraft to be fielded by 2018 that could meet certain stealth and speed requirements. Several major defense contractors

initiated programs designed to fulfill this new long-range strike requirement. The Northrop Grumman Corporation (NGC) design was unconventional, and consisted of a tailless aircraft that had a cockpit located well aft of a conventional cockpit location. The unique aspects of this Supersonic Tailless Air Vehicle (STAV) resulted in an instantaneous center of rotation (ICR) that was nearly collocated with the cockpit. This meant that the initial flight path response to a given pitch input would be opposite the direction of the input, an effect most pronounced to the pilot during approach and landing. This thesis research focuses on the unique handling qualities characteristics of the STAV during approach and landing.

1.3 Research Objectives

The primary objective for this thesis was to evaluate the handling qualities of the NGC STAV model and its flight control system during the powered approach and landing phase of flight, an objective supported by the various individual research objectives of three distinct test sections. These sections included research in the Infinity Cube Simulator (ICS), Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS), and the variable-stability Total In-Flight Simulator (TIFS) aircraft. The first two objectives involved the ICS testing, objectives three through five applied to LAMARS testing. The sixth objective was used in both LAMARS and TIFS testing, and the final two objectives concerned only the TIFS flight testing.

1.3.1 Objective 1 – Determine if piloting technique or background influenced how an aircraft's handling qualities were rated. This objective sought to reveal any differences in handling qualities ratings that resulted from different piloting backgrounds.

This included differences between pilots in service, type of aircraft flown, and test experience.

1.3.2 Objective 2 – Establish an overall test methodology to use in both simulator and flight testing at USAF Test Pilot School (TPS). The overall test methodology had to be conducive to both research at the Air Force Institute of Technology (AFIT) and to simulator and flight testing during TPS.

1.3.3 Objective 3 – Determine the best feedback control system (angle of attack, flight-path angle, or pitch rate) of the baseline STAV model. The baseline STAV model was the second version of the flight control system developed by the NGC to operate its supersonic tailless air vehicle. The model was capable of feeding back any one of the three parameters, and the pilots had to determine which produced the best handling qualities.

1.3.4 Objective 4 – Determine the baseline STAV model flying qualities as implemented on LAMARS. In order to make sure that the system under test in LAMARS was the same as the baseline STAV model, the flying qualities of the LAMARS simulation were compared with those of the baseline model. A good correlation between the two ensured the fidelity of the simulation.

1.3.5 Objective 5 – Develop an optimized flight control system, feel system, or technique to flight test in the TIFS in addition to the baseline STAV model. Based on the initial handling qualities results of previous NGC and ICS testing, new methods were employed to improve the perceived handling qualities.

1.3.6 Objective 6 – Compare the LAMARS optimized control system to the baseline STAV control system. The optimized system that employed the new methods

could then be compared to the baseline STAV control system to show any differences in perceived handling qualities. These systems were compared both in LAMARS and on TIFS.

1.3.7 Objective 7 – Determine the powered approach handling qualities of the baseline STAV model. The handling qualities of the baseline STAV model in flight were evaluated on TIFS during approach and landing.

1.3.8 Objective 8 – Determine the flying qualities for the TIFS simulation of the STAV flight control system. In order to make sure that the system under test in TIFS was the same as the baseline STAV model, the flying qualities of the TIFS simulation were again compared with those of the baseline model. A good correlation between the two ensured the fidelity of the simulation.

1.4 Research Overview

As shown in the previous research objectives, the research of this thesis was divided into three distinct test sections. The first section included research conducted at AFIT prior to attending TPS. While at AFIT, a group of nineteen different Air Force, Navy, Marine Corps, and civilian pilots conducted simulator testing in the ICS in an effort to address the first two research objectives. Each pilot conducted ten different approaches and landings in different aircraft models and assigned handling qualities ratings for each. The results were analyzed to determine any performance or ratings differences between the various pilots. The general test procedures employed in ICS testing were used as a framework for future testing during TPS.

During TPS, a group of three test pilots and three flight test engineers formed the HAVE STAV test team and addressed the remaining six research objectives of test

sections two and three. As mentioned in objective five, full-motion simulator testing in LAMARS was conducted to develop an optimized control system, feel system, or technique to flight test in TIFS in addition to the baseline STAV model. It also served to familiarize the test team with the baseline STAV model handling qualities prior to flight testing. Additionally, HAVE STAV conducted 160 different approaches and landings over sixteen hours of simulator testing. The team then analyzed the results for a month before the flight tests were conducted on TIFS at a Calspan facility in Niagara Falls, New York. During a week of flight testing six sorties encompassing sixty-seven different approaches for data were flown. The flight test data were analyzed and reported on prior to completing TPS.

1.5 Preview of Results

There were several significant results found during the conduct of this thesis. A brief synopsis of these major results follows, a more detailed discussion of these results can be found later on in this thesis.

The ICS testing showed that pilot background had an impact not only on the handling qualities rating, but also on the learning rate and the precision used to complete flying tasks. Overall, the pilot accuracy correlated well with the pilot rating, where the pilots who performed the best generally gave the best handling qualities ratings. The powered approach and landing tasks developed in the ICS and used throughout testing were demanding enough to test both the flight controls and the pilots while remaining operationally representative.

The LAMARS testing showed that the angle of attack (alpha-command) control system was favored by the pilots. The head STAV flight control engineer confirmed that

the flying qualities of the STAV as implemented on LAMARS were the same as those exhibited during previous NGC testing. The handling qualities of the baseline STAV model during the approach (above 300 feet AGL) were not problematic, and were considered satisfactory by the pilots. However, once below this altitude the handling qualities degraded, particularly when attempting to flare the STAV. All pilots noted that the flare was the most difficult part of a landing task. While the control system optimized in LAMARS still had a good number of inadequate landings and therefore unacceptable handling qualities, it displayed a marked improvement over the baseline STAV model.

For the TIFS flight tests, the handling qualities of the baseline STAV model during the approach (above 300 feet AGL) were again considered satisfactory by the pilots. Below this altitude the baseline STAV handling qualities remained predominantly unacceptable. The primary reason for these poor handling qualities was not a high pilot workload, but the inability of the pilots to meet the defined performance criteria. Both the pilot workload and compensation were deemed acceptable. The flare was again noted as the most difficult part of a landing task. The most objectionable flight control characteristic during a landing with the baseline STAV model was pitch sensitivity. The comparison of the LAMARS optimized control system with the baseline STAV control system showed that the optimized system had improved handling qualities over the baseline system. The number of landings which achieved desired performance nearly tripled, while the number of inadequate landings decreased by thirty percent. Despite this increase in performance over the baseline system, the optimized system still had almost twice as many unacceptable landings as satisfactory landings. These results indicated that the optimized system, while better than the baseline system, still had major

deficiencies requiring improvement. Overall, the TIFS aircraft was able to effectively match the flight characteristics represented by the STAV equations of motion. This illustrated the fact that although the aircraft did not yet physically exist, the STAV handling qualities could be determined using the TIFS.

1.6 Thesis Overview

The first chapter of this study introduced the purpose and motivation behind this thesis. It outlined the research objectives of each test section and provided a brief overview of the research conducted during the thesis. It then previewed the results of the thesis research before providing an overview of the thesis itself.

Chapter 2 of this research contains descriptions of and background information about the assorted topics related to this thesis research. It depicts and explains various handling qualities ratings scales including the Cooper-Harper rating (CHR) scale, and discusses when and where each could be used. It then details the impetus for and research behind the next generation of long-range strike aircraft, focusing on the 2006 QDR and NGC's STAV design. The related research of the cranked-arrow delta wing F-16XL program and the Space Shuttle/ TIFS program are then discussed. Several aerodynamic concepts that impact the handling qualities during powered approach are then detailed, including: static and dynamic longitudinal and lateral/ directional aircraft stability, dynamic inversion in flight controls, instantaneous center of rotation, and the power required curve. The two different pilot-in-the-loop simulators used during this research are then described, followed by the histories behind several different variable stability aircraft.

The different methods and procedures for conducting this study's test research are outlined in Chapter 3. The discussion first focuses on the scope and assumptions of this thesis. It then covers the overall general test methodology, including the initial test procedures developed using the previous LAMARS testing by the NGC. It also describes the specific integration of the different STAV models and the test specific procedures for each portion of the testing: ICS testing, LAMARS testing, and TIFS flight testing. These test specific procedures included both the tasks and test cards that each pilot flew as well as the desired parameters and constraints used in each test section. Finally, the data analysis plans for the test results of each section are all explained in detail.

The results and analysis of all testing are contained in Chapter 4. It is again divided into the three main test sections: ICS testing, LAMARS testing, and TIFS flight testing. It summarizes the pool of pilots for the ICS testing and shows who participated in each portion of the testing. It breaks down the results of the ICS section first by aircraft, then into overall HQ rating and data precision, and finally by HQ rating and data precision according to pilot classification. For the LAMARS and TIFS testing, it looks at results of the baseline and LAMARS optimized models, as well as the comparison between the two. The results include pilot performance and CHR for all three test sections and pilot workload vs. aggressiveness for the LAMARS and TIFS testing. Each section discusses: if the pilot ratings differed according to classification; ways to improve the test results; and any issues that hindered the tests or proved to be poor assumptions.

Chapter 5 is a summary of the entire thesis research, and includes both conclusions from the data and recommendations for the future. The chapter is again divided into the three main test sections: ICS testing, LAMARS testing, and TIFS testing.

The conclusions are drawn from the complete data analysis, and provide the most salient points to take away from each section. The recommendations consist of things that can be done to refine or expand the testing, as well as possible areas for future research to explore. The chapter shows when the recommendations of one test section were used in another, as well as when they were not followed due to outside constraints or limitations.

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2.0 Background

2.1 Overview

This chapter contains background information about different topics related to this thesis research. It depicts and explains various handling qualities ratings scales including the Cooper-Harper rating (CHR) scale, and discusses when and where each could be used. It then details the impetus for and research behind the next generation of long-range strike aircraft, focusing on the 2006 QDR and NGC's STAV design. The related research of the cranked-arrow delta wing F-16XL program and the Space Shuttle/ TIFS program are then discussed. Several aerodynamic concepts that impact the handling qualities during powered approach are then detailed, including: static and dynamic longitudinal and lateral/ directional aircraft stability, dynamic inversion flight controls, instantaneous center of rotation, and the front and back side of the power required curve. The two different pilot-in-the-loop simulators used during this research are then described, followed by the histories and descriptions of several different variable stability aircraft.

2.2 Handling Qualities Rating Scales

Before a discussion of handling qualities evaluations or pilot rating scales can begin, both concepts need to be defined in further detail. What are handling qualities? The terms flying qualities (FQ) and handling qualities (HQ) were sometimes used interchangeably. In the 1930's the U.S. Army Air Corps designer's handbook summed up flying qualities specifications in a single sentence: "The stability and control characteristics should be satisfactory" (Liebst-MECH 629, 2006). A USAF Test Pilot School (TPS) textbook defines flying qualities as: "Those stability and control

characteristics which influence the ease of safely flying an aircraft during steady and maneuvering flight in the execution of the total mission" (DoD-TPS, 2002). Cooper and Harper state that: "Handling qualities are those qualities or characteristics that govern the ease and precision with which a pilot is able to perform the tasks required in support of the aircraft role" (Liebst-MECH 529, 2006).

Although the terms are still sometimes used interchangeably, flying qualities and handling qualities are different. The pilot-aircraft system can be divided into two categories: those times when the pilot is out of the loop (an open-loop system), and those times when the pilot is in the loop (a closed-loop system). For a completely open-loop system, where the pilot is not included, the stability and control characteristics of an aircraft define the flying qualities of that aircraft. The characteristics of both the pilot and aircraft working together in a closed-loop system define the handling qualities of that aircraft. Flying qualities requirements are met by properly modeling and designing the flight control system to make the bare airframe appear to have the same characteristics as a historically desirable aircraft. Handling qualities mainly deal with the aircraft mission performance, and have the most impact on how a pilot will rate an aircraft. Handling qualities are rated at three primary levels (MIL-STD 1797B, 2006). Level 1 HQ are satisfactory, and are adequate to complete the mission. Level 2 HQ are acceptable, but with some increasing pilot workload and/ or degradation in mission performance. Level 3 HQ mean that while the aircraft is controllable, the pilot workload is excessive or mission effectiveness is inadequate.

The ability to measure and record a pilot's opinion of how well an aircraft flies is vitally important. It allows a pilot to evaluate a specific aircraft for its operational

suitability, or to record how well a certain configuration performs so that it can be used to help future designers (Hodgkinson, 1998). The simplest way to collect pilot opinion is via a pilot comment card, where the pilot answers questions about certain flying tasks. This is useful when conducting small-scale tests, but when working with large numbers of test configurations or pilots, a numerical record of preference is preferred. This record takes the form of a rating scale, where pilots are able to quantify their subjective opinion of a certain aircraft. The unique challenge of a handling qualities evaluation is that a pilot's opinions are not used as engineering data. The rating scales are used as a way of summarizing the opinions into an evaluation.

2.2.1 Cooper-Harper Rating Scale

Now that handling qualities have been defined and discussed, how can pilots quantitatively use them to rate aircraft in a repeatable manner? HQ rating scales provide the answer to the problem but there are several to choose from. "The Cooper-Harper scale is the most commonly used numerical rating scale" in flight test, and "is universally used to enable the pilot to award a number to an aircraft to allow comparison with other aircraft or to show compliance with a specification" (Hodgkinson, 1998). It is this commonality and universal acceptance among test pilots that drove the decision to use the Cooper-Harper scale throughout the course of this study.

When George E. Cooper from the National Aeronautics and Space Administration (NASA) and Robert P. Harper Jr. from Cornell University combined their research in 1966, the Cooper-Harper rating (CHR) scale came into existence. In 1970 it was adopted as the basis of the US flying qualities Military Specification, Mil-F-8785B. The Cooper-Harper scale has ten different points, where a 10 represents the worst HQ possible and a 1

represents excellent HQ. "The scale is dichotomous, which improves repeatability by leading the evaluation pilot through a series of decisions regarding the task performance and the pilot workload" (Hodgkinson, 1998). A pilot's analysis of these qualities through the rating scale is then used to either evaluate aircraft operational effectiveness or to match favorable characteristics with various aircraft configurations in an effort to improve the overall design. The Cooper-Harper scale is shown in Figure 1, and details the various pilot decisions made throughout the course of a test evaluation. Each decision leads to a yes or no answer, there is only a single way to reach a certain CHR level. The scale describes not just the pilot's decision tree, but whether improvements are necessary, what the aircraft characteristics are for each level, and how that corresponds to pilot workload. The scale was designed for its repeatability over a vast set of test conditions.

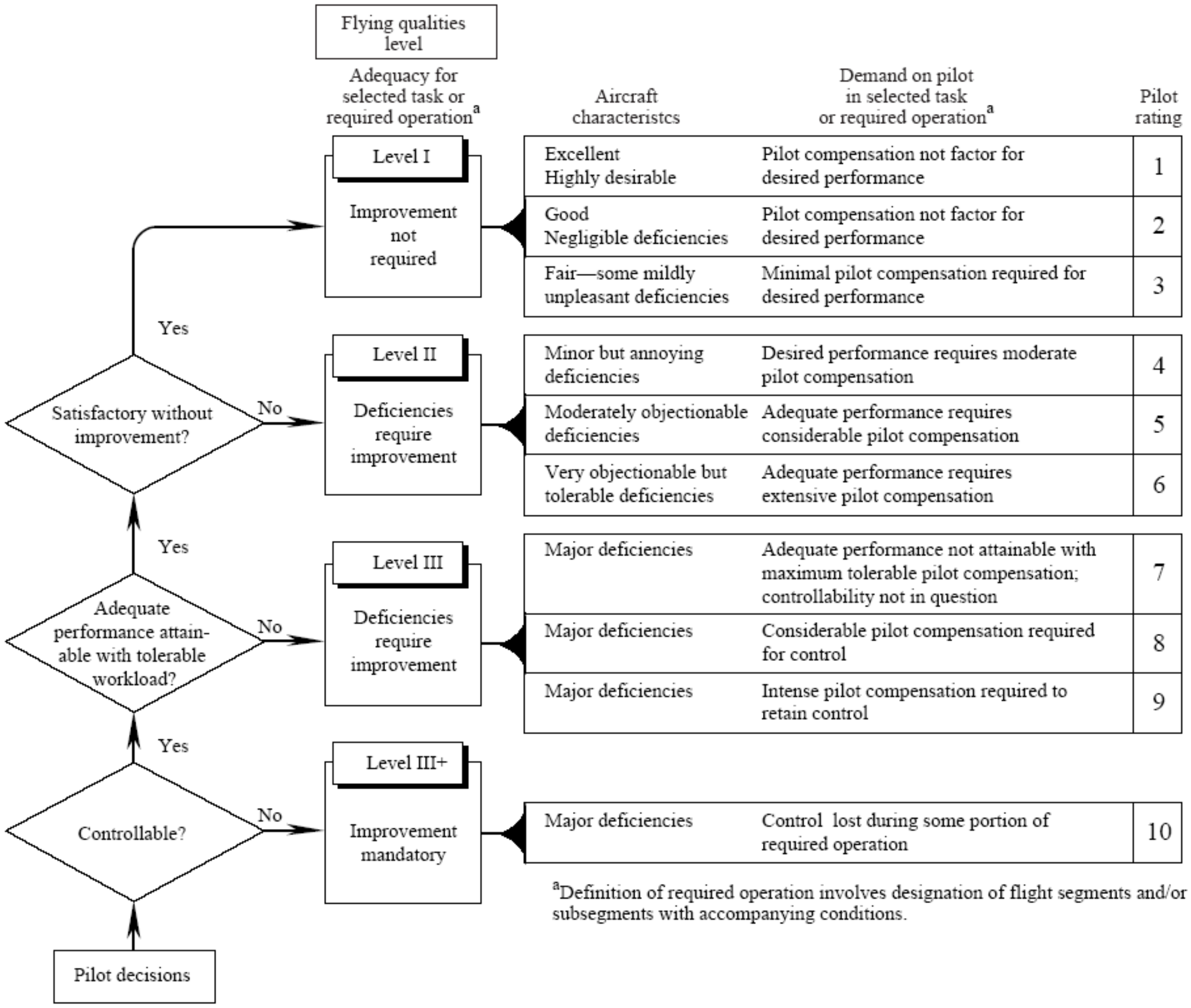

Figure 1 – Cooper Harper Rating Scale

2.2.2 Pilot In-the-loop Oscillation (PIO) Rating Scale

There are several other handling qualities scales besides the Cooper-Harper scale. The Pilot In-the-Loop Oscillation (PIO) rating scale is depicted in figure 2. It is a specialized scale directed at HQ problems that are known or suspected to cause PIOs. This scale is widely used in the test world, but its ratings can be scattered more than Cooper-Harper ratings, due mostly to the difficulty in describing if a PIO is an annoyance. The principle purpose of this scale is to initiate discussion on the topic of

PIOs between engineers and pilots. Following the PIO scale figure is table 1, which depicts the individual rating number and corresponding description.

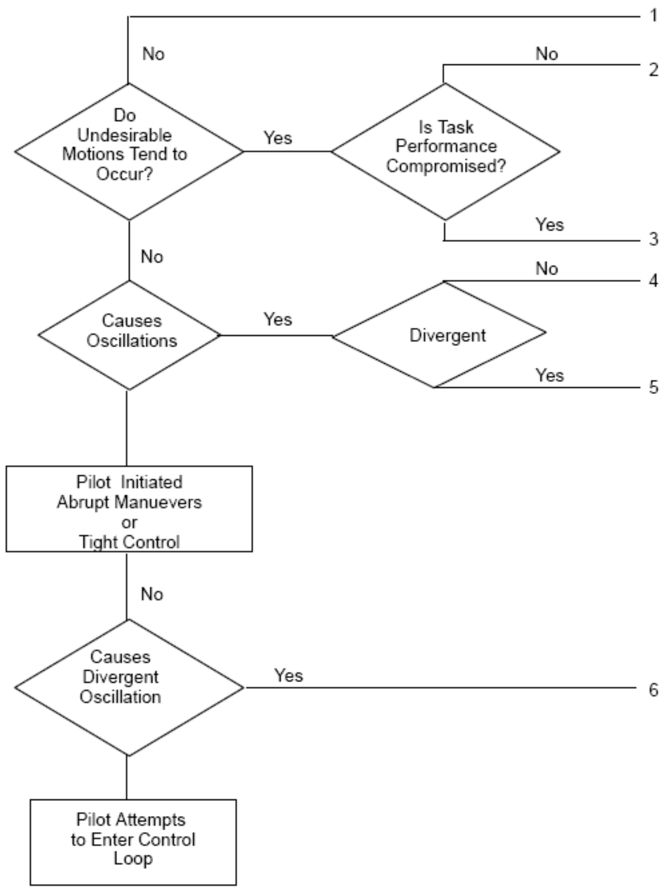

Figure 2 – PIO Rating Scale

Table 1 – PIO Ratings and Descriptions

Description	Rating
No tendency for pilot to induce undesirable motion	1
Undesirable motions tend to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique.	2
Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated but only at sacrifice to task performance or through considerable pilot attention and effort.	3
Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.	4
Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must open-loop by releasing or freezing the stick.	5
Disturbance of normal pilot control may cause divergent oscillation. Pilot must open control loop by releasing or freezing the stick.	6

2.2.3 Failure Rating Scale

In circumstances where the Cooper-Harper decision matrix is not straight forward in application another scale may be required. An example of this type of scale is the Failure Rating scale (Hodgkinson, 1998), shown in figure 3. This scale was developed at NASA Ames for evaluating failures and recoveries.

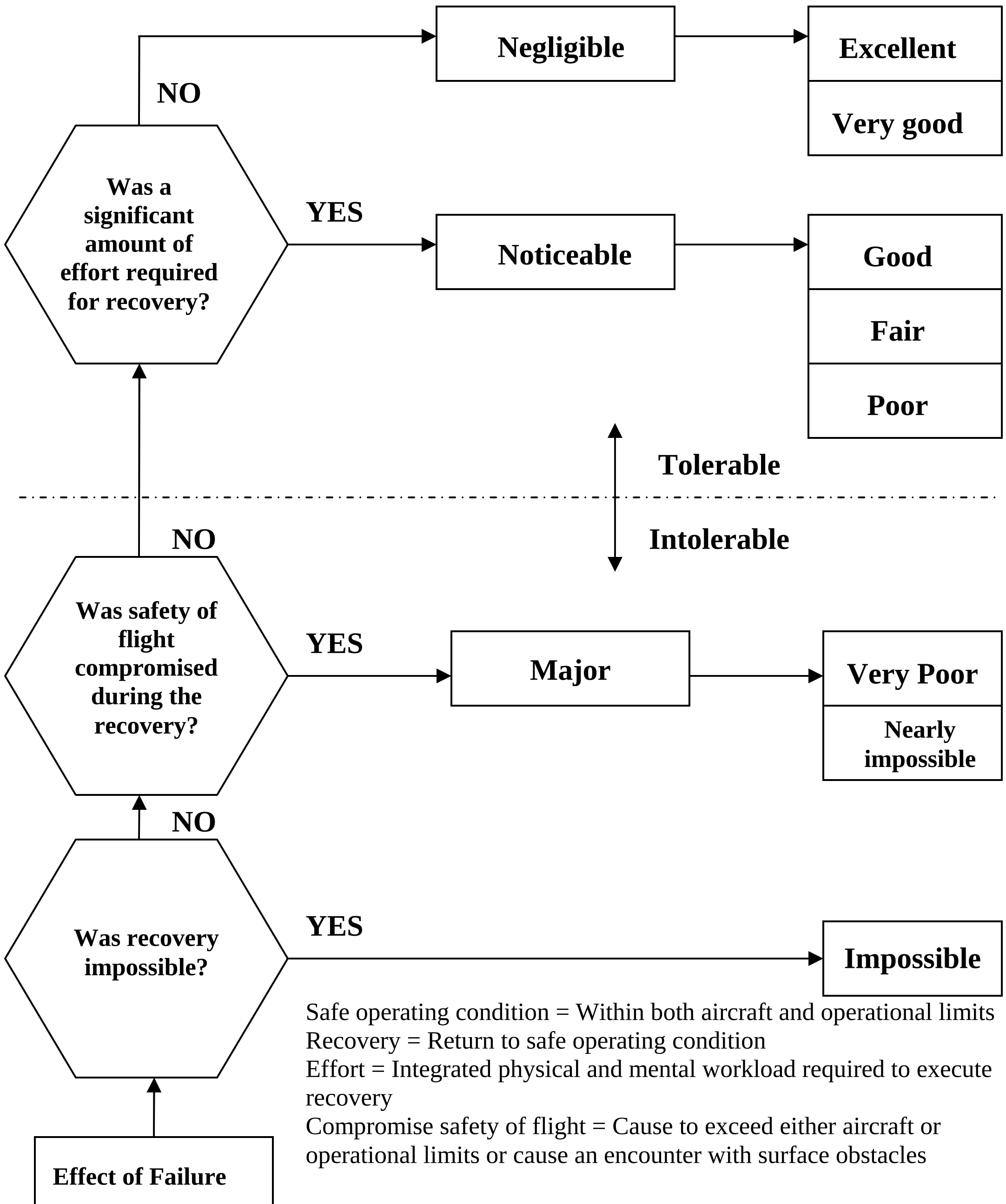

Figure 3 – Failure Rating Scale

2.2.4 Other Pilot Rating Scales

The particular objectives of a handling qualities evaluation will vary, and the research may need to incorporate other ratings scales that are more useful when conducting a specific type of testing. Some other examples of pilot rating scales are displayed in figures 4-6 to show just a few of the many choices available for rating the handling qualities of an aircraft. Figure 4 shows two Useable Cueing Environment scales

(Hodgkinson, 1998). These scales are designed to measure the level of pilot-vehicle interaction. An example of this is synthetic vision use in a cockpit, where these scales can measure how well necessary cueing information is provided to the pilot, and how that information impacts the pilot's assessment.

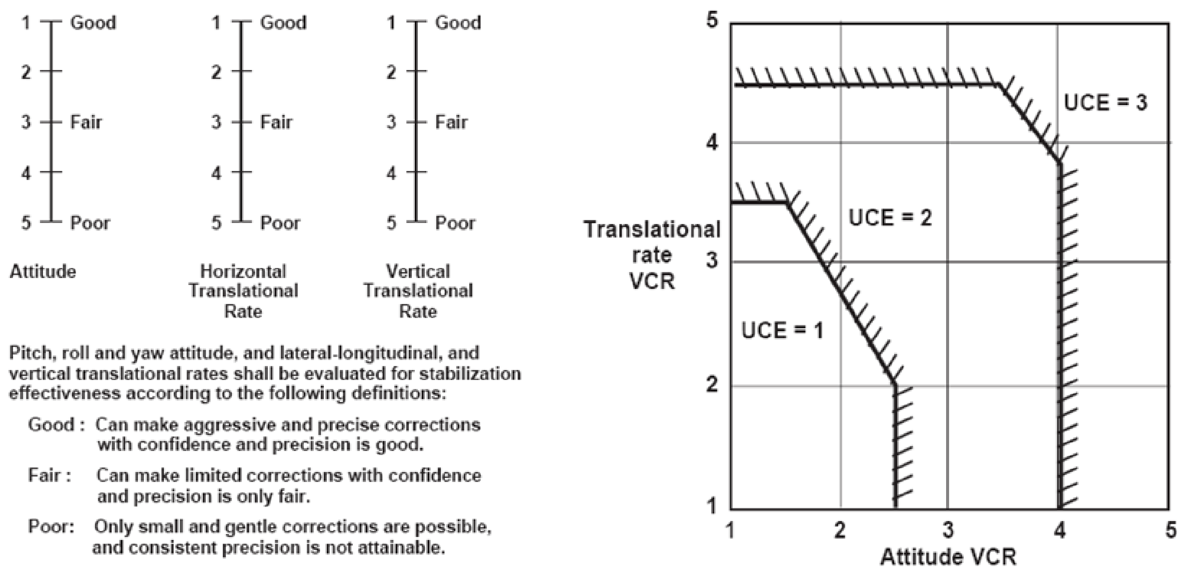

Figure 4 – Useable Cueing Environment Scales

The rating scale in figure 5 shows the level of situational awareness of the pilot while performing certain tasks (Hodgkinson, 1998). Situational awareness is the concept of being able to observe the present and remember the past in order to predict the future. Absolute situational awareness would allow an individual to observe and understand everything in their surroundings, correlate that information with events that have already occurred, and then make a conclusion about what will subsequently take place. A general rule is that as pilot workload increases, situational awareness decreases. This scale can be used to actually rate situational awareness, or can be used in combination with another rating scale in an effort to measure pilot workload.

China Lake SA Rating Scale

SA SCALE VALUE	CONTENT
VERY GOOD 1	• Full knowledge of a/c energy state/tactical environment/mission; • Full ability to anticipate/accommodate trends
GOOD 2	• Full knowledge of a/c energy state/tactical environment/mission; • Partial ability to anticipate/accommodate trends; • No task shedding
ADEQUATE 3	• Full knowledge of a/c energy state/tactical environment/mission; • Saturated ability to anticipate/accommodate trends; • Some shedding of minor tasks
POOR 4	• Fair knowledge of a/c energy state/tactical environment/mission; • Saturated ability to anticipate/accommodate trends; • Shedding of all minor tasks as well as many not essential to flight safety/mission effectiveness
VERY POOR 5	• Minimal knowlege of a/c energy state/tactical environment/mission; • Oversaturated ability to anticipate/accommodate trends; • Shedding of all tasks not absolutely essential to flight safety/mission effectiveness

Figure 5 – China Lake Situational Awareness Scale

Another pilot rating scale is the USAFAM Workload scale of figure 6 (Hodgkinson, 1998). As the name suggests, it is a measure of the pilot workload, or how highly tasked the pilot feels when trying to accomplish a certain scenario. As pilot workload increases, mission effectiveness will begin to decrease, and if raised to a high enough level, will impact the ability to maintain flight.

1	NOTHING TO DO; No system demands
2	LIGHT ACTIVITY; Minimum system demands
3	MODERATE ACTIVITY; Easily managed; Considerable spare time
4	BUSY; Challenging but manageable; Adequate time available
5	VERY BUSY; Demanding to manage; Barely enough time
6	EXTREMELY BUSY; Very difficult; Nonessential tasks postponed
7	OVERLOADED; System unmanageable; Essential tasks undone; Unsafe

Figure 6 – USAFAM Workload Scale

2.3 Next-Generation Long-Range Strike Aircraft

This thesis investigates a concept aircraft designed to meet the Air Force requirement for a new long-range strike capability. This section explains the impetus for the new aircraft and one defense contractor's efforts to design it. Although several contractors generated designs in response to the new requirement, this thesis looks only at one design concept, Northrop Grumman Corporation's Supersonic Tailless Air Vehicle (STAV).

2.3.1 2006 Quadrennial Defense Review

The US Department of Defense (DoD) conducts a review of its vision and mission every four years in order to better focus its efforts in a rapidly changing world. A result of this work was the 2006 Quadrennial Defense Review (QDR) report. The

2006 QDR was especially poignant, because it was the first QDR conducted in the post-September 11th world, while the nation was at war. It details the manner in which the DoD will fight the “Long War”. It states: “Joint air capabilities must be reoriented to favor systems that have far greater range and persistence; larger and more flexible payloads for surveillance or strike; and the ability to penetrate and sustain operations in denied areas. The future force will exploit stealth when and where it is needed. The Air Force has set a goal of increasing its long-range strike capabilities by 50% and the penetrating component of long-range strike by a factor of five by 2025. Approximately 45% of the future long-range strike force will be unmanned. The capacity for joint air forces to conduct global conventional strikes against time-sensitive targets will also be increased. To achieve the future joint force characteristics, the DoD plans to develop a new land-based, penetrating long-range strike capability to be fielded by 2018” (QDR, 2006).

2.3.2 Northrop Grumman Corporation Design Program

In response to the 2006 QDR, the Northrop Grumman Corporation (NGC) began a design program to meet the needs of the USAF. This program included several different concepts, including a long-range strike (LRS) aircraft and two regional bombers. These aircraft were designed to meet all mission threshold range and speed goals set by the Air Force. This resulted in design concepts that differed from conventional strike aircraft in several ways. First, to meet stealth and speed requirements, these supersonic aircraft had no tails. Second, the cockpit location was well aft of a standard cockpit location for structural reasons designed to reduce drag. Third, driven by the stealth requirement, crew visibility out of the cockpit was extremely

limited, meaning that most, if not all, of the pilot visibility outside the cockpit would have to be synthetic. Finally, the instantaneous center of rotation (ICR) of the aircraft was located far forward of a conventional aircraft's center of rotation. Rather than being located near the center of gravity (CG), the ICR was thirty feet in front of the CG, almost collocated with the cockpit. This meant that the initial flight path response to a given pitch input would be opposite the direction of the input. This response would be most pronounced to the pilot during approach and landing, where an input to climb would initially result in motion towards the ground. Furthermore, the sink rate perceived by the pilot in the cockpit would be much less than the actual sink rate of the landing gear, resulting in a potentially dangerous rate of descent.

All of these non-conventional design aspects combined to form an aircraft with a supersonic tailless delta configuration. Figure 7 shows an artist's rendering of a potential Supersonic Tailless Air Vehicle (STAV). Such vehicles are known to be aerodynamically complex aircraft with distinctive flight dynamic characteristics and intricate flight control laws. Therefore, a handling qualities evaluation of this aircraft was important to ensure that the aircraft control laws and flight control system had been properly designed and modeled.

Figure 7 – Supersonic Tailless Air Vehicle

The Northrop Grumman Corporation came up with several different flight control suites to use in the various concept aircraft (Northrop Grumman, 2007). The control suites consisted of control effector layouts of different size and type. A study on the stability, control, and aero-performance of high lift-to-drag ratio supersonic tailless air vehicles was conducted to determine which suites met requirements and provided the best aerodynamic and survivability solutions. Wind-tunnel tests were conducted to ensure that the different control effector layouts and flight control laws were being properly modeled and to aid in the creation of pilot-in-the-loop fixed-base simulations. These fixed-base simulations were then used to update the models, flight control laws, and address any control interference or power deficiencies. Three NGC test pilots and two USAF pilots conducted over fifteen hours of evaluations of control power gains and piloting techniques. These techniques included both front and back side of the power curve piloting techniques. This allowed the selection of the control effector suite that could be used in the entire STAV flight envelope. Full-motion simulations could then be used to explore control law design and different control effectiveness challenges. In order to accomplish this and to conduct a STAV/ LRS handling qualities assessment, NGC combined with Air Force Research Laboratory's Air Vehicles Directorate

(AFRL/RBCD) to conduct these full-motion simulations on the five degree-of-freedom Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS). Figures 8-11 depict the heads down display, attitude direction indicator, and heads up display (HUD) used during the test simulations, as well as the LAMARS itself.

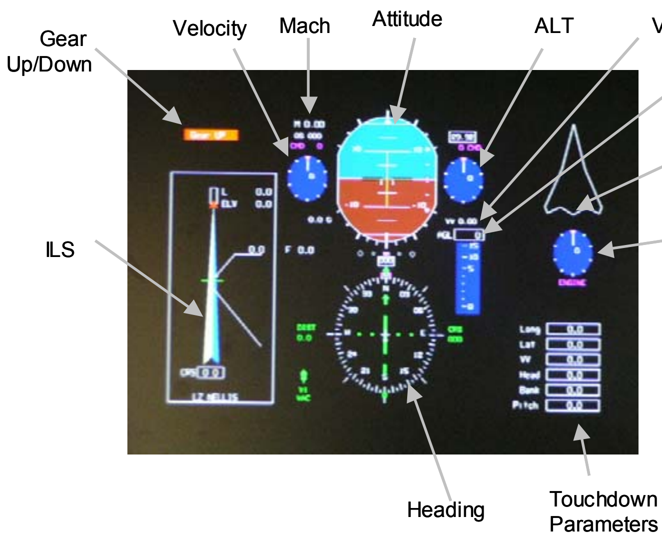

Figure 8 – Heads Down Display

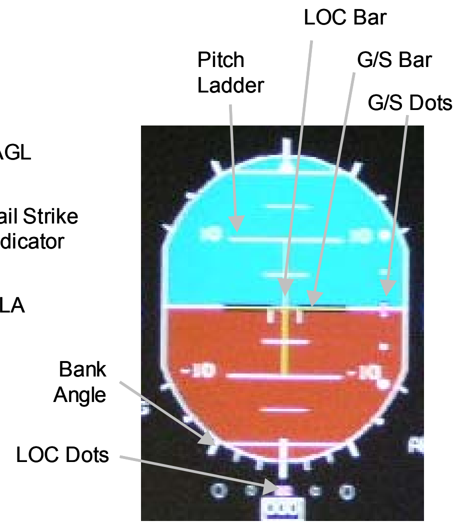

Figure 9 – Attitude Direction Indicator

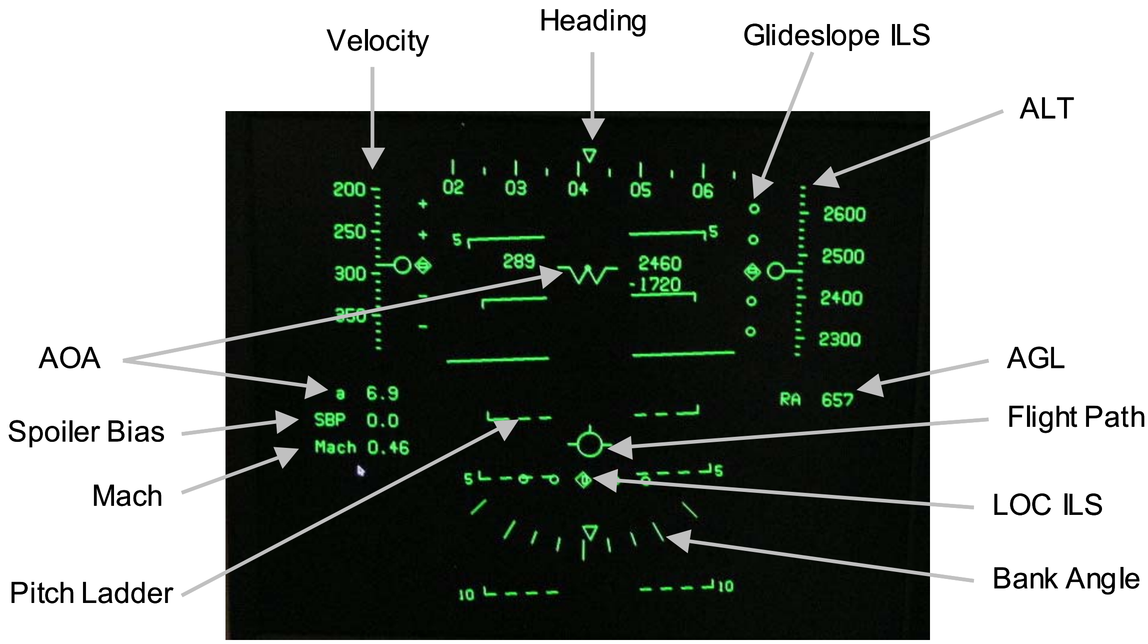

Figure 10 – Heads Up Display

Figure 11 – LAMARS at Air Force Research Laboratory

This full-motion testing involved five pilots (including the author) flying over 400 simulations runs covering forty-eight different test scenarios at Mach 2+ supersonic, subsonic up-and-away, and powered-approach and landing flight conditions. Testing revealed that the control laws and aerodynamic effectiveness of the control surfaces were stressed the most during the low-speed approach and landing test conditions. Test

scenarios were also completed using "synthetic vision" displays in place of the "out-the-window" cockpit view. The following table 2 displays the various test scenarios, defined as tasks, which included tracking and precision landing tasks in visual flight rules, instrument flight rules, and crosswind conditions.

Table 2 – Initial LAMARS Test Scenarios

Task	Task Name
Approach and Landing Tasks	
1	Nominal ILS Approach
2	Precision Landing
3	Lateral Offset Landing
4	Vertical Offset Landing
5	Go-Around
Low Altitude Cruise Tasks	
1	Attitude Capture (Theta) in Low Altitude Cruise
2	Heading Change in Low Altitude Cruise
3	Steady Heading Sideslip in Low Altitude Cruise
Supersonic Cruise Tasks	
1	Altitude Capture in Supersonic Cruise
2	Attitude Capture (Theta) in Supersonic Cruise
3	Heading Change in Supersonic Cruise
4	Steady Heading Sideslip in Supersonic Cruise
Synthetic Vision Tasks	
1	Nominal Synthetic Vision ILS Approach
2	Lateral Offset Landing with Synthetic Vision

The pilot ratings and comments from this battery of tests showed that STAV was not yet a "level one or level two" aircraft in most flying conditions. The pilots experienced some non-minimum phase behavior in pitch and yaw, which could result in a Pilot In-the-loop Oscillation (PIO) prone aircraft. However, the NGC concluded that with improvements to the control laws coupled with additional aids to alleviate pilot workload, these ratings could improve. It was apparent to them that the existing control effector suite was likely capable of delivering "level one or high level two" handling qualities throughout the STAV flight envelope. Further testing would include STAV

simulations with an improved flight control model that included ground effect in the low speed flight regime.

2.4 Related Research

Two other sources of research that involve the testing and handling qualities evaluations of supersonic semi-tailless air vehicles are the F-16XL program and the Space Shuttle Orbiter program. Both of these aircraft differ from the STAV, because they each possess a large vertical tail. However, they are similar to the STAV due to their lack of any horizontal tail and semi-delta wing configuration. Of particular interest is the Space Shuttle Orbiter's instantaneous center of rotation, which like the STAV is located far forward of a conventional center of rotation.

2.4.1 F-16 XL

The F-16XL program began in the early 1980's when two F-16s were modified by extending their fuselage length and incorporating a large area delta wing planform. What started as a derivative fighter evaluation program turned into an ability to test concepts in support of future high-speed supersonic transport aircraft (Stachowiak, 2004). This included an attempt to reduce drag by achieving natural laminar flow through careful contouring of the wing surface and active laminar flow control using an internal suction system built into the wing (Anderson, 1992). In order to expand the capabilities of this test platform, the aircraft was updated with a digital flight control system (DFLCS). A handling qualities analysis of the F-16XL with DLFCS incorporated commenced in December of 1997. Throughout the course of ten test flights, the Cooper-Harper HQ rating scale was applied to collected flight data, and compared with qualitative pilot assessments of the HQ (Stachowiak, 2004). The flight tests included

various handling qualities tasks: normal acceleration, pitch attitude, and bank angle captures, air-to-air tracking, close trail formation flight, and powered approach. Cooper-Harper HQ assessments were made for each task, from both a gross acquisition and fine tracking standpoint. A picture of the F-16XL taken during flight-testing is depicted in Figure 12.

Figure 12 – F-16XL in Flight

2.4.2 Space Shuttle Orbiter/ Total In-Flight Simulator (TIFS)

The Space Shuttle Orbiter program began in the 1970's and has been constantly tested throughout its life. It was designed to return to earth not via parachute as the Mercury, Gemini, and Apollo programs had, but by gliding back to land on a runway. The shuttle was equipped with an automatic landing program, because the space shuttle (like other gliders), only had one chance to land during recovery from space. The designers then set about attempting to provide a manual landing capability for an

operational crew and vehicle returning from orbit, just in case the automatic landing program was not working. Manually landing the orbiter in an operational environment proved exceedingly complex to accomplish, particularly due to the longitudinal handling qualities of the vehicle. This was due in large part to the fact that the instantaneous center of rotation of the orbiter was located in front of the actual vehicle. This provided a non-minimum phase response, where the flight path initially moved opposite to a given longitudinal input, a flight characteristic that caused concern for an un-powered aircraft close to the ground. Test flights of the orbiter involving approach and landing tasks indicated a tendency to PIO near landing, as demonstrated in a 1977 test landing before the Prince of Wales at Edwards AFB. The task of landing was made easier by changing the operational procedures, and an adaptive stick filter was employed on the orbiter to reduce the magnitude of any encountered PIOs. The evaluations included tests in fixed-base, full-motion, and in-flight simulators. The orbiter control system and procedures provided satisfactory performance in conducting precision landings with a large, low lift-to-drag ratio glider. Figure 13 shows the space shuttle Atlantis landing after a mission in 1988.

Figure 13 – Space Shuttle Atlantis Landing

In the mid-1980's, a new control system designed to improve the orbiter longitudinal response characteristics was investigated. This system improved the orbiter flight path response by increasing the amount of pitch rate overshoot and reducing the overall time delay. The NASA Ames-Dryden Flight Research Facility conducted test simulations of the shuttle during landing using the Ames Research Center vertical motion simulator and the Total In-Flight Simulator (TIFS) variable-stability aircraft. During these tests, it became evident that pilot background characteristics were influencing their opinion of the new orbiter's HQ rating. Trained and experienced astronauts who were familiar with the old control system found the new system to be inferior, while pilots without extensive training or experience on the shuttle strongly preferred the new system. The cause of this difference in rating was hypothesized to be the different control strategies of the two pilot groups. These control strategies were interpreted in terms of open-loop aircraft response characteristics and pilot-vehicle closed-loop characteristics (Powers, 1986).

2.5 Impacts on Handling Qualities during Powered Approach

The pilot's perception of an aircraft's handling qualities is impacted by numerous factors. The handling qualities can be more accurately evaluated if the pilot is able to discern why the aircraft responds in a certain manner. This section details concepts particularly important when evaluating a highly-augmented aircraft in the approach and landing environment.

2.5.1 Longitudinal Stability

Before discussing longitudinal stability specifically, it is important to define several terms that will be used in the discussion. The first is angle of attack, α, which is the angle made between the body-fixed axis pointing out the nose of the aircraft and the tangent to the flight path at the aircraft center of gravity. The flight path angle, γ, is the angle made between the velocity vector of the aircraft center of gravity and the horizon. Finally, the pitch angle, θ, is the angle made between the body-fixed axis pointing out the nose of the aircraft and the horizon. Pitch and flight path angles both reference the earth and are inertial, while angle of attack can be determined using the relation $\alpha = \theta - \gamma$. Illustrations of all three angles can be found in Nelson (Nelson, 1998).

The tendency of an aircraft to return to pitch equilibrium after encountering a disturbance in angle of attack is the definition of static longitudinal stability. If a disturbance pitches the aircraft nose up, then a longitudinally statically stable aircraft will produce a nose-down pitching moment. For static stability, this means that the moment coefficient due to angle of attack, $C_{m\alpha}$, is negative. If the pitching moment is zero, then the aircraft is longitudinally trimmed. In order to fly, a conventional aircraft must trim at a positive angle of attack and be longitudinally statically stable. This is normally done

using the elevator on the aircraft tail. A tailless aircraft needs to use complex flight control effectors to maintain static longitudinal stability.

The neutral point of an aircraft is its aerodynamic center, the point at which the pitching moment is constant when angle of attack is varied. The static margin of an aircraft is the distance the center of gravity is in front of the aerodynamic center, and is directly proportional to $C_{m\alpha}$ (Hodgkinson, 1998). If the center of gravity is moved too far aft towards the aerodynamic center, then the aircraft will become longitudinally statically unstable. The final part of longitudinal static stability is speed stability. Stick-fixed speed stability is positive if larger and larger longitudinal nose-down stick deflections are required as the trim airspeed is increased. Stick-free speed stability is positive if larger and larger longitudinal nose-down stick forces are required as the trim airspeed is increased.

The dynamic longitudinal stability of an aircraft involves two main factors, the phugoid and short period flying modes of motion. In a conventional aircraft, these two modes are a good indication of what the handling qualities will be. The phugoid mode is a low-frequency motion that interchanges altitude and airspeed. It causes altitude, airspeed, pitch, and flight path oscillations while maintaining a nearly constant angle of attack. The magnitude of this motion is small, and is usually controlled simply by the pilot's normal pitch inputs. However, if poor phugoid characteristics are present, more pilot compensation will be required, making non-flying tasks more difficult to complete. The following table shows phugoid damping ratio, ζ_p, requirements (MIL STD 1797B, 2006) and how they relate to handling qualities levels. The time-to-double amplitude, $T_{\theta 2}$, is the time it takes for the magnitude of the phugoid motion to double in size.

Table 3 – Phugoid Damping Ratio Requirements

Handling Qualities Level	Phugoid Damping Ratio Required
1	$\zeta_p > 0.04$
2	$\zeta_p > 0.0$
3	$T_{\theta 2} > 55$ seconds

The longitudinal mode of motion with the greatest impact on handling qualities rating is the short period mode. The short period governs the transient response of pitch, flight path, and angle of attack to a rapid control input or wind gust (Hodgkinson, 1998). During the short period oscillations, which are generally under-damped and stable, the airspeed and flight path remain nearly constant while the pitch and angle of attack vary. Although the duration of the motion is brief, it has a significant impact on the handling qualities rating. The following table shows the required short period damping ratio, ζ_{sp}, for different handling qualities levels and flight phase categories (MIL STD 1797B, 2006).

Table 4 – Short Period Damping Ratio Requirements

	Category A and C Flight Phases		Category B Flight Phases	
HQ Level	Minimum ζ_{sp}	Maximum ζ_{sp}	Minimum ζ_{sp}	Maximum ζ_{sp}
1	0.35	1.30	0.30	2.00
2	0.25	2.00	0.20	2.00
3	0.15	-	0.15	-

A pilot's ability to control the short period depends not only upon the mode itself, but also on the pitch response of the aircraft. The Control Anticipation Parameter (CAP), takes into account both of these. It is defined as the ratio of the initial pitch acceleration to the final normal acceleration. In an aircraft with good CAP, the initial and final accelerations perceived by the pilot will match the pilot's expectations. CAP is proportional to the square of the short period frequency, ω_{sp}. The CAP and ζ_{sp} can be

plotted against one another to predict the aircraft handling qualities levels. There are several other concepts that involve longitudinal dynamic stability in feedback control systems, including: equivalent systems and time delay, bandwidth and Neal-Smith methods, and drop-back criterion. Hodgkinson (Hodgkinson, 1998) delves into further discussion of these topics.

2.5.2 Lateral/ Directional Stability

Unlike longitudinal motions, which can be considered two-dimensional, lateral/ directional motion is usually seen as more complex. This arena involves roll, yaw, and side translation degrees of freedom. In order to simplify the discussion of lateral/ directional stability, the angles of roll, yaw, and sideslip require explanation. The roll angle, ϕ, is the angle made between the axis out the right wing of the aircraft and the horizontal, and is considered positive when the right wing is down. The yaw angle, ψ, is the angle between the axis pointing out the nose of the aircraft and an arbitrary reference azimuth line, and is considered positive as the nose moves right. The sideslip angle, β, is the angle made between the aircraft plane of symmetry and the relative wind flow direction. If this incident flow is encountering the right side of the aircraft, then sideslip is considered positive. Illustration of these angles can again be found in Nelson (Nelson, 1998).

If the aircraft response to an increase in sideslip angle is a restoring moment putting the aircraft nose into the relative wind, then that aircraft is directionally statically stable (positive $C_{n\beta}$). If the aircraft response to a nose-right sideslip is a left wing-down roll, then that aircraft is laterally statically stable, and is said to have positive dihedral

(negative $C_{l\beta}$). Lateral/ directional static stability is simply a steady-state case of dynamic stability.

Lateral/ directional dynamic stability includes three different modes of motion, the roll, Dutch roll, and spiral modes. The roll mode depends highly on the taper and aspect ratios of the aircraft wing. When an aircraft rolls, the roll inertia induces a resisting moment that is proportional to the product of the roll acceleration and the roll inertia itself. This resisting, damping moment is caused mainly by the aircraft wing, because the down-going wing experiences a higher angle of attack and higher lift, resulting in the opposing moment to the roll. This roll mode time constant is around a second for fighter-type aircraft, any longer than this and the pilot would feel as if they were commanding roll acceleration rather than rate (Hodgkinson, 1998). The spiral mode is best described as a slow divergence from a disturbance in roll angle. If allowed to continue, a slightly unstable spiral mode would cause an aircraft to slowly spiral in a descending, turning motion. This motion is generally benign and easy for the pilot to control, and can be slightly unstable yet still allow level one handling qualities. The final mode is that of Dutch roll, an oscillatory short-period motion in roll and yaw. It is considered by pilots to be an annoying motion experienced in the roll or yaw response to a lateral or directional control input.

The lateral/ directional handling qualities rating given by the pilot is impacted by the roll angle to sideslip, or $\phi/\ \beta$ ratio. This ratio can be used to predict some of the lateral/ directional problems that a pilot might experience while in flight. If the ratio is low (less than one), then the Dutch roll cannot be damped with lateral control, and roll maneuvers will be imprecise due to lateral nose motion. If the ratio is medium (one to

two), then roll precision can be adversely effected by roll oscillations or "ratcheting" (Hodgkinson, 1998). If the ratio is high (greater than two), then unwanted roll oscillations may be caused by turbulence or rudder inputs. The handling qualities of a given aircraft depend upon both static and dynamic longitudinal and lateral stability factors.

2.5.3 Dynamic Inversion

An aircraft's flight control system can significantly impact its HQ. One flight control method used by NGC on its STAV flight control system will be briefly discussed. NGC used a modern aircraft control theory called dynamic inversion as part of their design for the STAV flight control system. With dynamic inversion, a specific set of desired dynamics is used to replace the existing, undesirable dynamics. It can be used for either non-linear, single-input-single-output or multiple-input-multiple-output systems, provided that the respective control effectiveness function or control influence matrix is invertible (Shankar, 2003).

The dynamic inversion technique inverts the dynamic equations of the aircraft plant in an effort to specify the desired plant behavior. It accomplishes this explicitly by stipulating the rate of the control variable, rather than the control variable itself, where the control variable refers to the aircraft state being controlled (e.g. angle of attack). The undesired dynamics are cancelled and replaced algebraically using detailed selection of the feedback function. Dynamic inversion is also known as feedback linearization based on this process. The key assumption of this control theory is that the aircraft plant dynamics can be modeled well, and can therefore be cancelled out completely. If the

plant cannot be modeled well, then the new aircraft dynamics will require a robust controller to suppress any undesired dynamic behavior.

The ultimate goal of dynamic inversion is to find a controller such that the control variable will behave as desired. Consider the following example of dynamic inversion in flight control. The non-linear six degree-of-freedom model is described by the function $\dot{x} = f(x,u)$, where the states are defined as *x* and the control inputs are defined as *u*. The control variable is the variable to be controlled and is a nonlinear function of the state, *CV = h(x)*, where h(x) is a scalar function. The control variable rate can then be defined as $C\dot{V} = \frac{d}{dt}CV = \frac{d}{dt}h(x) = \frac{\partial h(x)}{\partial x}\frac{dx}{dt} = \frac{\partial h(x)}{\partial x}\dot{x} = \frac{\partial h(x)}{\partial x}f(x,u)$. Then, setting $f_2(x,u) = \frac{\partial h(x)}{\partial x}f(x,u) = C\dot{V}$, the control law $u = g(x, C\dot{V})$ can be obtained by solving for *u* in the nonlinear equation $f_2(x,u) = C\dot{V}$. The control variable rate, $C\dot{V}$, is then set equal to the desired rate, $C\dot{V}_{desired}$, that ensures the desired *CV* response. Assuming the state can be measured, so $x = x_{measured}$, the commanded input is given by $u_{command} = g(x_{measured}, C\dot{V}_{desired})$. A more comprehensive discussion of this topic can be found in the Honeywell report (Honeywell, 1996).

2.5.4 Center of Rotation

An aircraft's center of rotation is the point on an aircraft about which all moments or rotations take place. The typical location of this point corresponds with the vehicle's center of gravity, the point which represents the average location of the mass of the aircraft. The rotations about this point include those in each of the three dimensions of pitch, roll, and yaw. In a conventional aircraft design, the pilot is located forward of the center of gravity and thus the center of rotation. Given a command by the pilot, the

initial flight path response is in the same direction as the long-term aircraft response. When the pilot commands a pitch-up, the aircraft will respond by pitching its nose up. In these cases, the instantaneous center of rotation (ICR) closely matches the overall center of rotation. The following figure illustrates the center of gravity location and different axes of rotation.

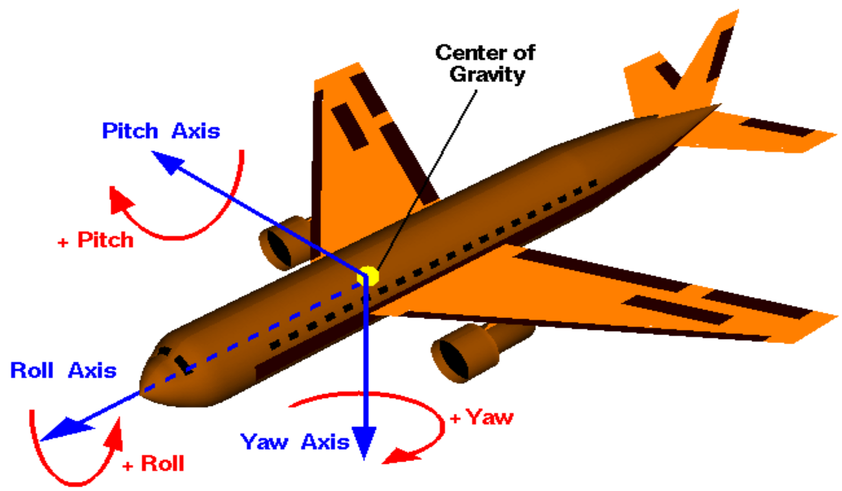

Figure 14 – Aircraft Body Axes and Rotations

In more advanced, unconventional aircraft with multiple control surface locations, the aircraft's ICR can be placed using blending of the control surfaces (Field, 2002). If the pitch ICR is placed in front of the center of gravity (CG), the initial flight path response at the center of gravity will be in the opposite direction of the long-term flight path response. The greater the distance between the aircraft's ICR and CG, the larger the disparity between the two responses will become. This difference in response is most pronounced to pilots during demanding phases of flight, such as powered approach and landing situations.

The ability to make consistent landings near the desired touchdown point is the pilot's main objective during approach and landing. In order to accomplish this, the pilot must be able to predict and accurately control the main gear's sink rate during the landing flare (Field, 2002). The pilot also needs sufficient cues about the flight path response at the main gear location to succeed in this task. If the initial and long-term responses are in opposite directions, it makes it more difficult for the pilot to predict what the flight path response will be for a given input, and makes the task of flaring the aircraft at the proper time extremely challenging. Aircraft with forward ICR locations near the pilot position, such as the Concorde or Space Shuttle, are known to exhibit poor flight path control characteristics in the landing flare. This tendency produces a negative impact on the handling qualities rating of the aircraft. This negative effect is further enhanced if the pilot is located far from the center of gravity, because the sink rate cues experienced by the pilot are different from the actual sink rate at the main gear location. The ICR location must therefore be carefully chosen to minimize the negative impact on the pilot while maintaining the desired aircraft capabilities.

2.5.5 Power Required Curve

The power required curve is established from the recognition that in level, un-accelerated flight, lift equals weight and thrust equals drag. Power is defined as the rate of doing work, which is a force times a velocity. In this level, un-accelerated flight regime, the power must balance with the drag force multiplied by the aircraft velocity. If the total drag curve of an aircraft is multiplied by velocity, then a plot of power versus airspeed can be formed, also known as the "power required" curve. This curve is usually defined from the minimum controllable airspeed, or stall speed, to the maximum level

flight speed. The total drag and power required curves will differ, because the former is a function of velocity squared and the latter is a function of velocity cubed. This concept is most simply explained using the following example. If velocity is doubled, then drag will increase by four times, and power required will increase by an eight-fold measure. This is why an increase in power from an 80% to a 100% setting does not show a corresponding increase in velocity. The following figure illustrates an example of a power-required curve.

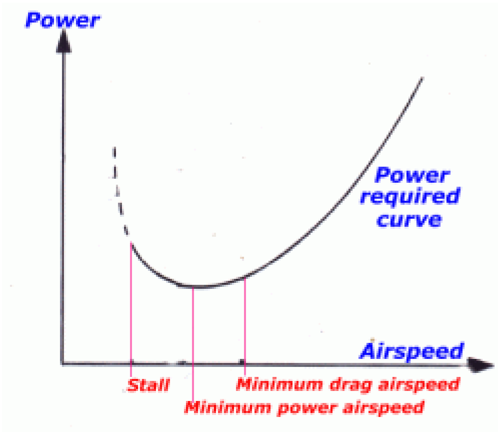

Figure 15 – Power Required Curve

This curve can be used to clarify the concepts of the front and back side of the power curve. The back side of the power curve is the portion of the curve to the left of the minimum power airspeed (Brandon, 2006). In this region of flight, slower speeds require more power, due to the increased induced drag associated with high angles of attack at low airspeeds. The stall speed represents the slowest possible airspeed for controlled flight. The front side of the power curve is that portion of the curve to the right of the minimum power airspeed, and is the flight region where most aircraft spend the majority of their time. The next figure adds the power available curve to power required plot.

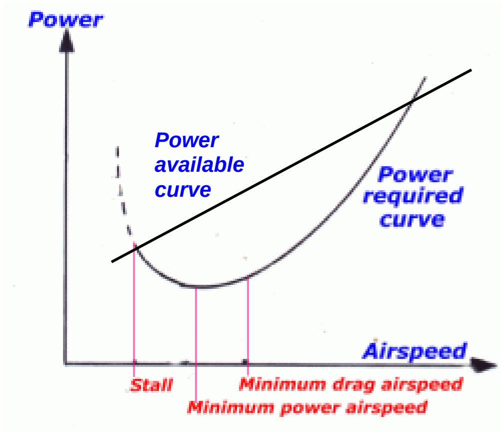

Figure 16 – Power Available vs. Power Required Curves

Thrust produced by a jet engine is relatively constant over an aircraft's airspeed envelope, and when multiplied by velocity represents the power available to an aircraft. The two power curves intersect at two different points. The point to the left is the point of stall. At airspeeds slower than this speed, the power required exceeds the power available, and the aircraft would be unable to maintain flight. The point of intersection to the right represents the maximum level flying airspeed of the aircraft. The aircraft is unable to fly faster than this airspeed in level flight, because the power required once again exceeds the power available. As aircraft altitude increases, the power available curve shifts down, until there is only one point where the two curves intersect. This altitude is known as the absolute ceiling of the aircraft, and is the highest altitude that the aircraft can maintain steady, level, un-accelerated flight.

As was mentioned earlier, aircraft spend the majority of their flight time on the front side of the power curve. However, in certain flight conditions, such as powered approach and landing, an aircraft may fly on the back side of the power curve. The piloting techniques associated with flying on each side of the power curve are opposite to one another. Pilots flying the back side technique use aircraft pitch to control airspeed

and power to control flight path. If the pilot wants to go faster, instead of increasing the throttle position, the pilot will drop the nose of the aircraft. If the pilot wants to climb, they will increase the throttle setting while leaving aircraft pitch unchanged. This technique is backwards to the normal flying convention, and the back side of the power curve is therefore termed the “region of reverse command”. The front side piloting technique is the standard for flying. Pitch is used to control flight path, and power controls airspeed. In simple fighter parlance, “pull back on the stick and the houses get smaller, push forward on the stick and the houses get bigger.”

Although most pilots, regardless of service, spend most of their flight time on the front side of the power curve, there are differences between the services, particularly in the realm of powered approach and landing. Air Force pilots will tend to stay on the front side of the power curve, because it represents a safer region of flight. If a wind gust slowed the aircraft down in this region, the power required would decrease, and the pilot would be able to correct back to a normal flying airspeed. However, in the region of reverse command, that same wind gust would cause the power required to increase, and if this new power required exceeded the power available, the aircraft would not be able to maintain flight. Due largely to the requirement to land on aircraft carriers, US Navy and Marine Corps pilots tend to fly powered approaches and landings on the back side of the power curve. The decreased airspeed allows the aircraft to better land on the ship and catch the arresting cable. Approach and landing are demanding tasks for the pilot, and the piloting techniques used by the respective service pilots when conducting these operations tend to correspond to the techniques those pilots will fly when highly tasked in other flight conditions. The handling qualities of a new aircraft can be impacted by this

preference for one flying technique over another, and any HQ assessment should take this factor into account.

2.6 Pilot in-the-loop Simulation Platforms

During the course of this research two different ground-based simulation platforms operated by AFRL/RBCD were used, the Infinity Cube Simulator (ICS) and the Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS).

2.6.1 Infinity Cube Simulator (ICS)

The Infinity Cube Simulator was a fixed based simulator with a 200 degree horizontal and 120 degree vertical field of view. Images were collimated to between -0.11 and 0.0083 diopters to present a focus distance close to infinity (Dotter, 2007). The inceptor was a fixed-position force-sensing side stick that resembled an early model F-16 stick. The pilot would sit in the seat and slide into the simulator. A map light was available to provide needed illumination when making comments to the test cards. The test director and control room technicians communicated with the pilot via a headset. Simulator runs could be recorded with both video and audio for post-test analysis, as well as pilot inputs and aircraft parameters. Figure 17 depicts the Infinity Cube Simulator (Dotter, 2007).

Figure 17 – Infinity Cube Simulator

2.6.2 Large Amplitude Multi-mode Aerospace Research Simulator

The LAMARS was briefly discussed in section 2.3, and was depicted in figure 11. LAMARS was a five degree-of-freedom full-motion simulator. It had a simulation cockpit enclosed at the end of a thirty-foot arm that could move plus or minus ten feet horizontally or vertically. The simulation cockpit could achieve up to a 3g vertical or 2g horizontal acceleration, and could rotate plus or minus twenty-five degrees in roll, pitch, or yaw. The cockpit had both heads up and heads down displays available for use during testing, and also had the capability for either a center or side inceptor location. A control room looked over the simulation cockpit and arm assembly and had multiple displays depicting the aircraft parameters, heads up and heads down displays, and the pilot field of view, which was approximately 120 degrees horizontal by 40 degrees vertical. The projectors in LAMARS had been modified to produce a brighter image that provided more realistic imagery. There was also a safety camera that viewed

the pilot whenever the simulator was in motion. The test director and control room technicians communicated with the pilot via headset. Simulator runs could be recorded with both video and audio for post-test analysis. Electronic strip charts could display and record any desired aircraft parameters.

2.7 Variable Stability Aircraft

The use of a variable stability aircraft was vital to this research, and a brief historical description follows to provide the reader insight on the origins of these aircraft. In 1948, testing began to determine the ideal wing dihedral for the Ryan FR-1 Fireball. Three aircraft, each with their own wing dihedral, were built to determine the best design option. This process was not only labor and time intensive, but expensive. The desire for a better solution inspired William Kauffman to develop the concept of a variable stability aircraft. He postulated that the basic flight characteristics of an aircraft could be altered by a stability augmentation system, so that the handling qualities of several different aircraft, represented by a broad range of static and dynamic characteristics, could be simulated and tested in flight (Kauffman, 1949). Later that year, engineers at the Ames Aeronautical Laboratory modified an F6F-3 Hellcat to become the first variable stability aircraft ever constructed.

The variable stability system on this aircraft altered the effective wing dihedral by deflecting the ailerons in response to a sideslip. A modified control linkage allowed the pilot to conventionally control the roll axis without feeling the variable stability system-commanded aileron deflections. The aircraft was then used in general studies of lateral-directional flying qualities criteria and as an in-flight developmental aircraft simulator. This second characteristic allowed test pilots to determine a new aircraft's handling

qualities before it even flew. A prime example of this ability was the design of the F-104 Starfighter, whose negative dihedral wings were incorporated only after testing on the variable stability aircraft (Heinle, 1952).

In the 1950's high-performance swept-wing jet aircraft became the leading edge of aviation technology, and caused an evolution in variable stability aircraft, from the two-axis variable F-86 series of aircraft to the three-axis variable F-100C. A variable stability F-86A and F-86E were used to develop lateral-directional flying qualities for these new high-performance aircraft, while an YF-86D tested longitudinal characteristics. The F-100C became the last high-performance variable stability aircraft of the time (Borchers, 1998). The next generation of variable stability aircraft then began with the NT-33.

2.7.1 NT-33A

The NT-33A was a modified T-33 trainer sponsored by Wright Laboratory and used for in-flight simulations. The aircraft, tail number 0-14120, was delivered to the USAF in October 1951 and transferred to the Calspan Corporation, where it was modified into a variable stability aircraft in 1954. The NT-33A began its first engineering test flights in 1959, after various checkouts and modifications. It possessed an F-94 nose that enabled the housing of the flight control computers and recording instrumentation. The aircraft trained hundreds of test pilots to evaluate advanced aircraft and control concepts, analyze human factors concerns, and detect potential handling problems in new aircraft. Studies flown by the jet included handling qualities, pilot-vehicle interaction, and flight control analyses of the X-15, X-24, A-10, F-15, F-16, F-18,

F-117, and F-22, among many other American and foreign aircraft (Brown, 2001). The following figure 18 is a photograph of the NT-33A variable stability aircraft.

Figure 18 – The NT-33A Variable Stability Aircraft

The flight control system on the NT-33A was a three degree-of-freedom, response-feedback system that enabled independent control of the roll, pitch, and yaw of the aircraft. The flight control computer programmed the front cockpit flight controls to perform according to the simulation aircraft flight characteristics, so that the pilot would feel as if they were flying different simulation aircraft. A safety pilot in the rear cockpit had standard controls, which allowed them to fly the aircraft in case of a computer malfunction or if the simulation aircraft became too demanding to control. The aircraft conducted its last research in April 1997, when it retired with the most flying hours of any active USAF aircraft. It is now on display at the National Museum of the United States Air Force.

2.7.2 NC-131H TIFS

The need arose for another variable stability aircraft that would allow testing of the flight characteristics of larger aircraft. Calspan, under a Cooperative

Research and Development Agreement, was tasked to develop the U.S. Air Force Flight Dynamics Directorate NC-131H Total In-Flight Simulator (TIFS) Aircraft. This aircraft was used to conduct the flight testing of this research. Figure 19 shows the TIFS variable stability aircraft in flight.

Figure 19 – Total In-Flight Simulator in Flight

The TIFS aircraft was developed in the late 1960's under Air Force Flight Dynamics Laboratory sponsorship in an effort to help develop new aircraft and to advance simulation technology for HQ research. The Federal Aviation Administration's (FAA) interest in simulating Super Sonic Transport (SST) landing visibility also helped initiate the project. Calspan performed modifications to an Air Force-furnished C-131B to convert it into an in-flight simulator. A separate simulation cockpit, additional control surfaces, computer-controlled hydraulic actuators, and turbo-prop engines were all added. The final aircraft, designated an NC-131H, first flew in July 1970. The turboprop engines and propellers were replaced in 1992 and 1994 to provide better performance and maintainability. The TIFS was a highly modified Convair-580 (USAF C-131) twin turboprop transport, which was used as a six degree-of-freedom in-flight simulator for advanced flying qualities and display research. It was also used to demonstrate advanced

flight control concepts and avionics systems, and functioned as an avionics flying test bed in a separate configuration.

According to Calspan, "The TIFS unique features include a separate two-place evaluation cockpit and control over all six rigid-body degrees-of-freedom. Special aerodynamic controls (including side-force and direct lift surfaces) and a model-following control system permit the TIFS to produce motions at the simulation cockpit that completely duplicate the computed responses of the simulated aircraft. Its primary use has been in the development and evaluation of new aircraft flying qualities, flight controls, and cockpit displays, as well as general flight research in these areas" (Calspan 2005). The following figure 20 diagrams the capabilities and layout of the TIFS.

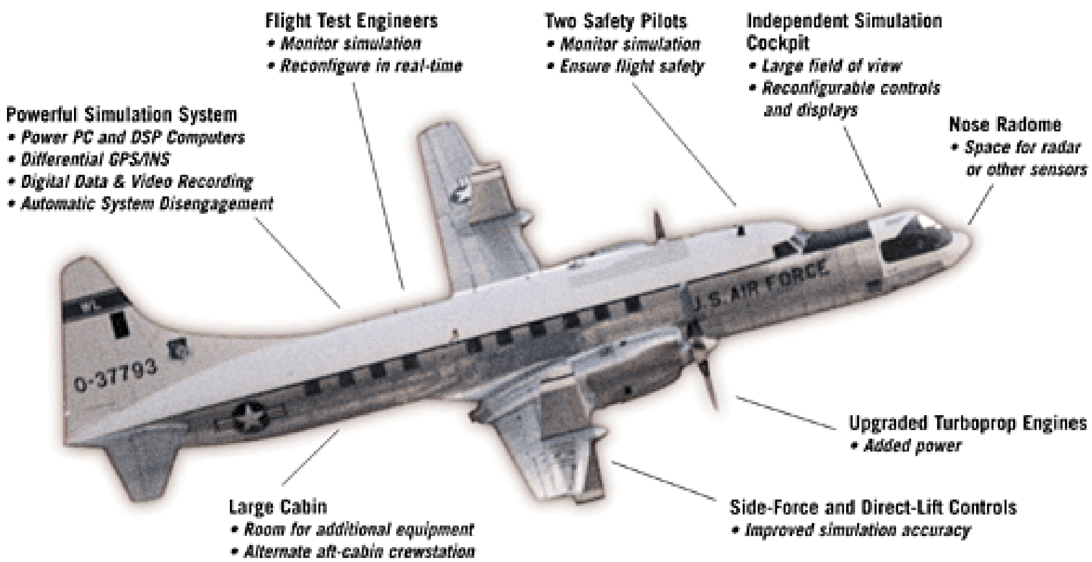

Figure 20 – TIFS Capabilities and Layout

The additional aerodynamic controls of the variable stability system (VSS) on TIFS included all-moving side-force surfaces on the mid positions of the wings, and direct lift flaps, which were outboard of the engine nacelles. These surfaces worked in combination with the conventional C-131 flight control surfaces, the throttle servos, and

the model-following system to provide full six degree-of-freedom control (rotational: roll, pitch, and yaw; translational: normal, axial, and side forces) that completely duplicated the computed responses of the simulated aircraft.

The Avionics Systems Test and Training Aircraft (ASTTA) was another configuration of TIFS with a large avionics nose that was interchangeable with the simulation cockpit nose (Peer, 1991). Developed in 1985, the ASTTA allowed the addition of customer-supplied large prototype radars, infrared cameras, or other sensors and equipment. The aft cabin included an instrumented crew station to accommodate system operators. In 1998, extensive modifications were made to the TIFS simulation cockpit to accommodate test equipment for the eXternal Visibility System program element of the NASA High Speed Research program (Babala, 1998) and the synthetic vision component of the Aviation Safety program. TIFS was fitted with a new nose cap and canopy to increase the simulation cockpit volume to accommodate the XVS display system and a Collins X-band radar (Calspan, 2005). The following figures 21-24 show the different TIFS and ASTTA configurations, as well as a view of the aft crew compartment.

Figure 21 – Front View of Dual-Cockpit TIFS Configuration

Figure 22 – Side View of Lower Cockpit in Dual-Cockpit TIFS Configuration

Figure 23 – View of Aft Crew Compartment inside TIFS

Figure 24 – TIFS with ASSTA Configuration Supporting Customer Hardware

The TIFS aircraft has been involved in numerous HQ assessments and research and development programs during its history. TIFS supported the Space Shuttle Orbiters in several programs, and took part in military aircraft development programs such as the B-1, B-2, Tacit Blue, X-29 and YF-23. Calspan itself best describes the aircraft's versatility: "Several supersonic transport aircraft and "million-pound" aircraft configuration programs for NASA and industry have employed TIFS for configuration and control system development, as well as for visibility and sensor investigations. TIFS has been used for human factors experiments on instrumentation; displays, control feel, motion cueing, and passenger ride sensitivity. The ASTTA configuration of TIFS has been a training platform for test pilots and engineers, and has been used for global positioning system (GPS), armament avionics, and remotely piloted vehicle development programs. The breadth of these programs illustrates the flexibility of the TIFS" (Calspan, 2005). The aircraft is currently maintained and operated for the US Air Force Research Laboratory by the Calspan Flight Research Group in Niagara Falls, New York. A complete detailed description of TIFS is in the TIFS reference (Calspan, 2005).

2.7.3 NF-16D (VISTA)

The final variable stability aircraft detailed in this thesis was the Variable-Stability In-Flight Simulator Test Aircraft (VISTA). This thesis originally planned to flight test on this aircraft, but it was unavailable. The NF-16D was delivered to the USAF in 1995, and has been operated by Calspan, the company who designed and installed its variable stability and other experimental systems, ever since. Originally based at Calspan's Flight Research Group in Niagara Falls, New York, it is currently flown and maintained at Edwards AFB, California. The USAF Test Pilot School and other customers worldwide use the aircraft as both a research and training tool. The aircraft provides many features, including: all-attitude five degree-of-freedom simulation capability; easily reconfigurable, fully instrumented programmable controls and displays; and an automatic safety monitoring system. A photograph of VISTA during a test flight is shown in figure 25 below.

Figure 25 – VISTA in Flight

In-flight simulations of prototype aircraft are accomplished from the front cockpit of the VISTA. However, the pilot does not require qualification in the F-16, because all pilot-in-command displays and controls are relocated to the aft cockpit, where the safety pilot monitors the flight. This safety pilot, backed-up by a quad-redundant automatic

VISTA Integrity Monitor, ensures that tests do not exceed the limitations of the simulation system or the aircraft itself. The following figure 26 diagrams the capabilities and layout of the VISTA.

Figure 26 – Capabilities of the Variable-Stability In-Flight Simulator Test Aircraft

The VISTA has a programmable simulation system that allows for efficient checkout of different software loads. Changes to the system do not require extensive verification and validation testing, because the simulation system is not critical to safety-of-flight. A suite of digital computers connected by dedicated 1553 data buses provides the "heart of the simulation system" (Calspan-VISTA, 2006). Aircraft parameters needed for testing are digitally recorded and can be transmitted in real-time via a telemetry downlink. VISTA can also integrate weapons systems and tactical display concepts into the simulations via wing hard points and APG-68 targeting radar. This aircraft has been a fundamental part of the developmental testing of cutting-edge aircraft, including the F-35 Joint Strike Fighter, the Indian Light Combat Aircraft, and the X-38. This variable stability aircraft represents a significant asset to the research and development of new fighter-type aircraft and their corresponding weapons systems.

2.8 Summary

This chapter sought to explain the background information that required understanding in order to fully comprehend this study. It began with a synopsis of handling qualities scales, including the Cooper-Harper rating scale, and detailed the use of each. It then detailed the impetus for and research behind the next generation of long-range strike aircraft, focusing on the 2006 QDR and NGC's STAV design. The related research of the cranked-arrow delta wing F-16XL program and the Space Shuttle Orbiter/ TIFS program were discussed. Issues that impacted handling qualities during powered approach were then covered. This included longitudinal and lateral/ directional aircraft stability from both a static and dynamic viewpoint and the concepts of dynamic inversion in flight controls, center of rotation, and the front and back side of the power required curve. The two ground-based pilot in-the-loop simulation platforms were then detailed. The chapter concluded with a historical review of variable stability aircraft, including detailed information on three of the most important: the NT-33A, the NC-131H TIFS, and the NF-16D VISTA.

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3.0 Testing Methods and Procedures

3.1 Overview

This chapter outlines the different methods and procedures conducted throughout this study's test research. The discussion first focuses on the scope and assumptions of this thesis. It then covers the overall general test methodology, including the initial test procedures developed during initial Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS) testing by the Northrop Grumman Corporation (NGC). It also describes the specific integration of the different Supersonic Tailless Air Vehicle (STAV) models and the test specific procedures for each portion of the testing: Infinity Cube simulator (ICS), LAMARS, and Total In-Flight Simulator (TIFS) flight tests. These test specific procedures included both the tasks and test cards that each pilot flew as well as the desired parameters and constraints used in each test section. Finally, the data analysis plans for the test results of each section are all explained in detail.

3.2 Scope/ Assumptions

The main factor in the formation and conduct of this thesis was the requirement for actual flight-testing of the thesis topic. This flight-testing would have to be conducted in accordance with the guidance set forth by the USAF Test Pilot School (TPS) test management project (TMP) program. The thesis topic would have to fulfill the requirements of both an AFIT thesis and a TPS TMP. The TMP to evaluate the STAV handling qualities was named project HAVE STAV. While a handling qualities evaluation of the entire STAV flight envelope would have been desirable, a program of such magnitude would have far exceeded the scope of this thesis and the flight test capabilities of a single TMP. Rather than provide some general qualitative assessment of

STAV handling qualities, this thesis focused on a handling qualities (HQ) evaluation of a specific low-speed region of flight, that of powered approach and landing. In order to fly this thesis, a variable stability aircraft capable of simulating the STAV flight dynamics and of conducting the desired flight tests had to be selected. Originally, this study planned on using the Variable-Stability In-Flight Simulator Test Aircraft (VISTA) at TPS, but this was not possible due to aircraft availability. The selection of the Total In-Flight Simulator (TIFS) as the test aircraft was subject to and met all of the cost, availability, and safety concerns involved in this flight-test program. The decision to use this aircraft helped to refine the desired test objectives to the ones used in the conduct of this thesis. Several other limiting assumptions were made to maintain both the scope and focus of the HQ evaluation of the STAV in this thesis.

All HQ evaluations, both qualitative and quantitative, were based off of the Cooper-Harper rating (CHR) scale, the primary rating scale used by modern USAF test pilots. Even though Cooper-Harper ratings are not normally averaged, for the purposes of the ICS testing it was assumed that the CHR could be averaged in order to statistically compare different pilot groups. For this research, the rating on the pilot in-the-loop oscillation (PIO) scale was assumed to be 1 unless a PIO was encountered or if a PIO-tendency was specifically noted by the pilot. There was no thrust vectoring used in the STAV model, and an initial 30% spoiler bias setting was used in all approach and landing tests. This value was selected because it provided the best speed stability on powered approach and landing during the full-motion simulations conducted by the NGC on LAMARS. The ICS was selected over LAMARS for the initial testing in this study because it provided better visual cues and capability in the powered approach and landing

arena, and was easier to use with a large group of pilots. These visual cues were assumed to have more of an impact on pilot opinion than the subtle motion cues experienced in LAMARS, especially on landing. All cockpit vision issues associated with angle of attack or cockpit location were not included in this testing. The side stick used in the Infinity Cube Simulator was considered to have minimal impact on the HQ evaluations conducted prior to TPS.

The testing throughout this study, including both simulation and flight testing, involved two different NGC long-range strike concept STAV models that used dynamic inversion as part of the flight control algorithm. The STAV model used in initial LAMARS and ICS testing did not include ground effect or gear modeling, which made the actual landing HQ of the STAV impossible to specifically determine. However, this evaluation was used to generate an approximate HQ rating for both approach and landing. The Version 2 STAV model, which from now on will be referred to as the baseline STAV model, included both ground effect and gear modeling and was tested in both LAMARS and TIFS. Although two different models were tested during the course of this thesis, it was assumed that results from testing the first model could be compared to results from the second model, particularly from a qualitative sense, and that lessons learned from initial testing could be applied to subsequent testing. For the purposes of this study, dynamic inversion was assumed to be a viable flight control option, and the structural issues associated with control surface movements were considered to have a negligible impact on the flight control system.

The pilots used throughout the test program were not all test pilots. The pilots available at the Air Force Institute of Technology (AFIT) encompassed a broad range:

from heavy to fighter, from zero to significant test experience, and from civilian to three different services. These varying backgrounds seemed to preclude repeatability in test data, so a technique was used to set a baseline for the ICS testing. General HQ information and CHR procedures were briefed to all pilots before testing. In addition to conducting an HQ evaluation of the STAV, these pilots also flew a T-38 model flying the same maneuvers. The T-38 model was a hi-fidelity model that included ground effect and had been tested to ensure it closely resembled actual T-38 flight characteristics. The pilots rated both aircraft, and their HQ evaluations were compared to historical information about the T-38 to establish a baseline for the non-test-pilot raters. It was assumed that this would allow a HQ evaluation by non-test-pilots to be comparable to an HQ evaluation conducted strictly by test pilots.

After beginning TPS, it became evident that the number of pilots able to participate in the HAVE STAV TMP would be limited to three, much less than the large pilot pool tested at AFIT. Also, the STAV model itself could not be altered due to proprietary reasons. However, the inputs going into the model could be altered, and the test objectives changed from testing different types of pilots to testing different control or feel systems. This minor migration in test objectives was assumed to enhance the overall scope and quality of the research.

Finally, the initial flight test matrix called for at least ten test flights to conduct the HQ evaluation on TIFS, but due to monetary and time constraints this was reduced to ten hours of flight time. These constraints also prevented the implementation of a Heads Up Display (HUD) in the TIFS cockpit. The decision was made to forgo a HUD in LAMARS as well, even though it had the capability to use one, so that the cockpit layout

in LAMARS would match that of TIFS. Testing in LAMARS and TIFS instead used a heads down display, accompanied by altitude calls from a test engineer. The flexibility in the test program allowed the TMP team to meet all of the flight test objectives with the limited flight test time.

3.3 General Test Methodology

In the spring of 2006, the Northrop Grumman Corporation (NGC) conducted LAMARS testing on a concept STAV, in an effort to evaluate the handling qualities at various high and low speed flight regimes. In order to accomplish this evaluation, three different test pilots and two other USAF pilots (including the author) were given a set of tasks to perform. These tasks were designed to be operationally valid maneuvers that a new strike aircraft would be expected to accomplish on a given mission. Each task had several performance metrics that measured the pilot's ability to successfully complete the maneuver. At the completion of each task, the pilot rated the handling qualities of the aircraft according to both the performance achieved and the workload required to accomplish the task. The tasks were then repeated at different airspeeds and altitudes in an effort to more completely explore the aircraft mission envelope. This initial NGC LAMARS testing served as the basis for the research conducted in this thesis.

The results from this initial NGC testing revealed that the control laws and aerodynamic effectiveness of the control surfaces were stressed the most during the low-speed approach and landing test conditions. It also showed that piloting technique seemed to play a large role in the perceived HQ. In response to these findings, a research effort was initiated by the author to continue low-speed approach and landing testing. The testing followed the same format as the initial NGC LAMARS testing, where a pilot

conducted a series of tasks and then rated the HQ based on the workload and performance achieved. The different STAV models provided by the NGC to AFIT and Calspan allowed the construction of several test profiles. These profiles were then tested in one of three platforms: the Infinity Cube Simulator at the Air Force Research Laboratory (AFRL) using a single throttle and side inceptor with the initial STAV model; the LAMARS full-motion simulator at AFRL using two throttles and a center inceptor with the updated (baseline) STAV model; and the NC-131H TIFS variable stability aircraft using two throttles and a center inceptor with the updated (baseline) STAV model.

The Infinity Cube Simulator testing focused on how different pilot backgrounds (i.e. time, type, service) influenced performance and HQ evaluations. In addition to the initial STAV model, a T-38 model was also tested, in order to set a baseline for all the pilots. This allowed the data to be reduced at both an overall ratings level and according to each pilot characteristic. This was done to reveal any trends or tendencies for certain pilots to rate similar tests differently.

As mentioned in the previous section, the focus of testing changed after the ICS to studying the impact of different control systems on HQ. This was due to the limited number of pilots on the HAVE STAV TMP team. Prior to testing in LAMARS, each HAVE STAV pilot flew the different test tasks in a TPS T-38 so that they could become familiar with them and validate that they were operationally valid and safe. The LAMARS was selected over the ICS by the TMP team so that a direct comparison of test data could be made with a second round of NGC LAMARS testing. Since the LAMARS testing was conducted in preparation for flight testing, the TMP team wanted a higher

fidelity simulation with motion, so that these motions could be compared to those experienced on TIFS. The LAMARS testing focused on familiarizing the HAVE STAV pilots with the baseline STAV model and on developing an alternate control or feel system that could be flight tested on TIFS and compared to the baseline STAV model. First, the flying qualities of the baseline STAV model as implemented on LAMARS were compared to those found in the second round of NGC LAMARS testing to ensure that the results closely matched. Then, the specific type of feedback control for the baseline STAV model was chosen, after which an alternate control system was optimized. This LAMARS optimized model was then compared to the baseline STAV model.

The TIFS flight testing also compared the flying qualities of the TIFS-implemented STAV model to the second round of NGC LAMARS testing, again to ensure that the model following was accurate to the predicted STAV response. Both the baseline and LAMARS optimized models were then flown and compared to see if the HQ were better with one model than the other. Once the data were reduced, observational and interpretive analysis was conducted to best summarize the test results for each test section.

3.4 Infinity Cube Simulator (ICS) Testing

In October of 2006, a series of simulator tests was conducted in the ICS by a group of nineteen pilots of varying flying backgrounds. The testing was divided into two phases, a preparation and an execution phase. During the preparation phase, the test tasks were defined and the overall test plan was developed. The test plan included a straight-in precision approach and landing task, a lateral offset landing task, and a vertical offset landing task. All tasks were designed to land the aircraft 1,000 feet down the runway on

centerline. During the precision approach task, the pilot had to maintain approach airspeed while flying down a specified glideslope. During each of the landing tasks, the pilots had to land within a designated zone on the runway while meeting different sink rate, airspeed, heading, and bank angle requirements. During the offset landing tasks, the pilots would maintain a course or glideslope that would result in either a lateral or vertical offset from the runway. At 300 feet above ground level (AGL), the pilot would either correct laterally back to runway centerline or would vertically correct to land the proper distance down the runway. These tasks were some of the same as those conducted during the initial NGC LAMARS testing, and also had almost identical performance criteria, which were set based off of previous research conducted during the high-speed civil transport program. The only performance criterion that differed was the touchdown sink rate, which was changed to higher values after looking at actual performance achieved during the initial NGC LAMARS testing. The tasks were designed to mimic the operational conditions of flying a precision instrument approach, a non-precision approach that brings the aircraft in offset with the runway laterally, and an approach where the aircraft breaks out of the weather at a higher than normal glideslope. As the tasks increased in difficulty, the pilot gain increased in an effort to reveal any poor HQ not evident in lower gain tasks. All tests would be flown with a 30% spoiler bias, meaning that the spoilers would be extended 30% at all times during the approach and landing. Previous testing showed this provided better speed stability and control during approach and landing.

After defining the tasks, a test plan was created that defined both test conduct and test goals. The test goals were to establish if piloting technique or background influenced

how the HQ were rated and to provide an overall test methodology to be used during the TPS curriculum. In order to determine the role piloting technique played on the perceived aircraft HQ, the approach and landing tasks were conducted at two different approach airspeeds, 175 and 195 knots. While these airspeeds were actually both on the back side of the power curve, they were set far enough apart to simulate both front and back side of the power curve conditions. The offsets used in the initial NGC LAMARS testing were used again, as they represented operationally valid maneuvers. The pilot pool at the Air Force Institute of Technology (AFIT) varied widely in background and experience. In order to establish some sort of baseline for all of the pilots, an aircraft with known handling qualities was used, the T-38. All of the tasks were accomplished flying both the STAV model and the T-38. After defining the tasks and scope of the test, a series of test cards was created. They each included the performance criteria for the task, the directions for accomplishing the task, and areas for pilot comments and Cooper-Harper rating. The ICS test cards are located in appendix C, figures C-1 through C-3.

The simulator used in testing, the ICS, was a fixed-base simulator that provided outstanding visuals over a 200 degree field of view. The ICS was selected over LAMARS for the initial testing in this study because it provided better visual cues and capability in the powered approach and landing arena, and was easier to use with a large group of pilots. These visual cues were assumed to have more of an impact on pilot opinion than the subtle motion cues experienced in LAMARS, especially on landing. Prior to the test execution, all of the pilots involved in testing were briefed in detail on the tasks, the performance criteria, and the simulator operation. Each pilot also received instruction on the CHR scale and how to use it. This instruction conformed to the

curriculum at the USAF Test Pilot School. The pilots were briefed that they would be flying two different flight control models; they were not told that one of the models was the T-38. That information was purposely withheld in order to maintain an unbiased opinion prior to testing. Each pilot was instructed to study the test tasks and the CHR scale prior to testing. In order to ensure the proper motivation levels, the pilots were briefed that the best and worst performers would be highlighted and revealed, a fact that produced nineteen well-prepared pilots.

In the week prior to testing, the T-38 and STAV models were loaded onto the ICS and calibrated. Due to modeling constraints and availability, an F-16 HUD was used with the T-38 model and a C-17 HUD was used with the STAV model. During the execution phase of testing, each pilot was in the simulator for approximately forty-five minutes. Whenever a new model was introduced, the pilots flew a practice approach and landing before conducting any approaches for data. The pilots were briefed on the HUD differences between the two models. The T-38 model was always flown first, and after the practice approach each pilot flew the precision approach and landing, lateral offset landing, and vertical offset landing tasks. The testing was conducted over a three day period, and the pilots were divided evenly each day according to their background. After flying the T-38 model at 175 knots, the STAV model was flown at 175 and 195 knots approach speed. Half of each pilot group flew the 175 knot approaches prior to the 195 knot approaches. The other half of each pilot group flew in the reverse order. This was done to counter any overall handling qualities improvement brought on solely by learning. The pilot comments and aircraft parameters were recorded for each test run on a computer file, an audio file, and a video file. For the approach task performance

criteria, the aircraft parameters when passing through 1000 feet AGL were recorded and used to ascertain pilot performance. For the landing tasks, the aircraft parameters at touchdown were used to measure pilot performance. After the pilots made comments and saw the performance achieved, they gave two CHR for each run, one for the longitudinal axis and one for the lateral axis. The two CHR were given to highlight any hidden HQ deficiencies that occurred in a specific axis. After completing all of the test tasks, each pilot was briefed to not discuss the testing with any other pilots until after all ICS testing was complete.

The data collected during the ICS testing was reduced and analyzed using a data analysis plan created prior to test execution. During testing, each data run was given a number, so that it could be more easily organized after test completion. On each data run, a hard copy of a test card was used by the test conductor to record pilot comments, initial performance parameters, and CHR. During testing, runs that were noted by the test conductor as particularly interesting were noted, so that they could be pulled from all the other runs after testing. The audio comments and performance achieved on each run were reviewed to make sure that the final CHR was proper. The computer files were recorded in a manner that they could be easily transferred to an Excel spreadsheet for data reduction. The data were divided first by aircraft, and then by each pilot group. The overall CHR and performance achieved in each aircraft was recorded for each task. The data were then broken down by pilot type, experience, and service. These three pilot classifications each had two groups: fighter and heavy for type, test and non-test for experience, and Air Force and Navy/ Marine Corps/ Civilian for service. Both Navy and Marine Corps pilots were considered to be Navy pilots, and the civilian pilot was

considered to be a heavy pilot. The data were analyzed to see if any pilot group rated the HQ vastly different from another group, or if they preferred a certain approach airspeed over another. It was also analyzed to see if one pilot group was able to fly with greater precision than another, and have better performance parameters. Each performance criterion was weighted equally and the pilot groups were compared using a term called parameter accuracy. The pilot groups were analyzed to see if one group learned faster than another (i.e. the STAV model CHR improved) as testing progressed. HQ results from initial LAMARS testing were compared to ICS testing HQ results. The aerodynamic characteristics of the STAV model, including factors like short period damping and phugoid time to double, were used to determine the predicted HQ of the STAV, which were then compared to the HQ found in testing. This analysis was then used to make conclusions and recommendations for the ICS testing.

3.5 LAMARS Simulator Testing

Testing of the STAV model was conducted by the HAVE STAV TMP team in the LAMARS full motion simulator on 6-7 August 2007. As mentioned previously, LAMARS was selected over the ICS so that a direct comparison of test data could be made with the second round of NGC LAMARS testing conducted in November 2006. Since the LAMARS testing was conducted in preparation for flight testing, the TMP team wanted a higher fidelity simulation with motion, so that these motions could be compared to those experienced on TIFS. The main objective was to identify an optimized flight control system, feel system, or technique to flight test on the TIFS in addition to the baseline STAV model. This simulator testing was used to familiarize the test team with the STAV model and test tasks prior to flight testing on TIFS. In order to better replicate

the capabilities of the TIFS cockpit, a center inceptor location was chosen and a HUD was not employed. The test cards used in LAMARS testing can be found in appendix C, figures C-4 through C-9. The tasks were the same as those used in the ICS except for the normal approach and landing task. This task became just a single evaluation, instead of an approach evaluation and a landing evaluation. Also, a sole CHR was assigned to each task, instead of a lateral and longitudinal CHR. All tasks were again designed to land the aircraft 1,000 feet down the runway on centerline. The performance criteria were also the same except for the sink rate criteria, which were decreased to account for the STAV landing gear structural capabilities. The STAV model tests all began with a 30% spoiler bias, for the same reasons mentioned previously.

A factorial design method (Montgomery, 2005) was initially used with four variables (pilot, offset, crosswind, and approach airspeed) to find the optimal test matrix where the most significant variable interactions would be identified. This matrix was executed on LAMARS by the TMP team to verify predictions and to narrow down the actual test matrix for flight testing. LAMARS testing was conducted by the TMP team in three phases. The first phase focused on an investigation of the flying qualities of the baseline STAV model and a comparison of the alpha, gamma, and q-command control systems. The test team used a series of impulses, steps, and semi-closed-loop capture tasks in each axis to determine the flying qualities of the baseline STAV model as implemented on LAMARS, and compared the results to those found in the second round of NGC LAMARS testing to ensure that the results closely matched. The second round of NGC LAMARS testing also investigated the angle of attack (alpha–command), flight-path angle (gamma-command), and a pitch-rate (q-command) control systems. It

indicated that the optimal flying qualities during powered approach and landing tasks were obtained using an angle of attack (alpha–command) control system. Each HAVE STAV pilot conducted a limited evaluation of the baseline STAV model with each of these control systems to determine which the best was and which warranted further investigation on TIFS. The pilots flew two or three practice approaches before flying the tasks for data. This procedure was done to familiarize the pilot with the sight-picture of the flare and pacing of the approach and landing. Each pilot developed a technique for accomplishing the flare during this first phase, after which the pilots decided on a standardized flare technique. Each pilot accomplished the precision approach and lateral offset tasks with and without crosswind, as well as a vertical offset landing task. These maneuvers were accomplished to see if offsets in different axes produced different workloads for the pilots. These simulations were accomplished using only a heads down display, because TIFS did not have a heads up display (HUD).

The initial and second rounds of NGC LAMARS testing revealed the powered approach and landing tasks that involved a lateral offset or high crosswinds demonstrated a high pilot workload and potential for pilot in-the-loop oscillation (PIO). The forward location of the instantaneous center of rotation and the associated flight path response was the likely reason for this PIO potential. As the pilot tried to make aggressive corrections back to the runway, the initial motion was in the opposite direction of the commanded motion in both pitch and yaw. In an effort to improve aircraft handling qualities, the effects of increasing longitudinal inceptor force gradients and the effects of spoiler retraction on flare characteristics were studied by the TMP team in phase two of LAMARS testing. An increased force gradient would reduce the tendency to over-

control, and the spoiler retraction would counter some of the moment generated when pulling aft on the inceptor, potentially shifting the instantaneous center of rotation and improving handling qualities during the flare.

This second phase involved modifying the feedback control system judged best during phase one of the testing. This modification involved automatically increasing the force gradient in the longitudinal axis when passing through a set AGL altitude. Both the value of the force gradient and the altitude of the gradient change were varied in order to yield a more repeatable and predictable flare. The first pilot to test the system conducted the test tasks while varying both the altitude and value of the force gradient change. The values judged best by the first pilot were passed on to the next pilot, who began with these values and altered them before passing them on to the next pilot. This process continued until the values were set to an optimized level. To determine the effects of spoiler retraction, the force gradient was reset to the baseline and the spoilers were automatically retracted when passing through a certain AGL altitude. The altitude of this retraction was optimized in the same manner as the force gradient changes, in an effort to achieve complete spoiler retraction as touchdown occurred. The two modifications were then made simultaneously, and the pilots again assigned a CHR according to workload and performance. The effects of both of these modifications on pilot opinion and performance were then compared to the baseline system.

The third and final phase focused on this comparison between the LAMARS optimized system developed in phase two and the baseline STAV control system. The optimized system was tested by all three pilots to ensure that they agreed that the chosen values for force gradient, spoiler retraction, and gradient change were all optimal. All the

pilots then retested the baseline system and compared their results to the previous baseline testing to ensure that any improvement in pilot opinion or performance could not be attributed to practice alone. A TPS staff pilot then flew both the baseline and optimized system in order to evaluate any differences between the two systems and corroborate or refute the test team results. The flight test engineers and flight test weapon systems officer then flew to familiarize themselves with what the pilots were feeling and to practice the test procedures to be used during flight testing.

The data analysis plan for the LAMARS testing was created by the TMP team prior to actual simulator testing. It sought to begin the data analysis concurrently with testing, so that the TMP team could adapt if the testing was not proceeding according to plan. This method was used to provide the most flexibility to the test effort, a crucial factor when dealing with a set test schedule. While at the LAMARS facility, copies were made of both the parametric data for each run as well as any audio or video recordings that were noted by the test conductor as particularly interesting. Each data run was given a number and a hard copy of a test card was used by the test conductor to record both pilot comments and initial performance parameters. A run number for all the programmed test inputs and semi-closed-loop maneuvers was also recorded during the flying qualities portion of testing. At LAMARS, a DVD of all the recorded parameters for each test run was made. While testing, excel spreadsheets were created to input Cooper-Harper ratings and performance data in order to get a real time quick-look of trend data on how the testing was proceeding. After LAMARS testing was completed, a brief was conducted to summarize the quick-look results and gather any preliminary lessons learned.

After returning to TPS, the data were analyzed in order to determine if the test objectives were met. The goal of the data reduction after LAMARS testing was to establish a data set to compare to TIFS testing and to prepare Matlab, Excel, and other data reduction techniques to streamline the effort when reducing TIFS data. For the first phase of testing, the flying qualities of the STAV model as implemented on LAMARS were analyzed. Additionally, the alpha, gamma, and q-command control systems were compared. For the second phase, the results from the model optimization were laid out. This included looking at the improvement in CHR as well as performance, and linking this improvement with the pilot comments. The analysis of the optimization sought to explain the reasons for the improvement. The results from the repeat testing of the baseline model were then analyzed to uncover any learning trends in the data. For the third phase, comparisons between the baseline and optimized system were made by plotting pilot aggressiveness and duty factor, as well as histograms of CHR for each system.

3.6 TIFS Flight Testing

Flight testing of the STAV model was conducted on the NC-131H Total In-Flight Simulator, a six degree of freedom in-flight simulator operated by Calspan. The flight test sorties were accomplished from 10-13 September 2007 in the airborne traffic pattern at Niagara Falls International Airport. The goal of flight testing was to meet all three of the test management project (TMP) team objectives: determine the powered approach handling qualities of the baseline STAV model, compare the LAMARS optimized control system to the baseline STAV control system, and determine the flying qualities for the TIFS simulation of the STAV flight control system. The primary objective for this thesis

was to evaluate the handling qualities of the STAV flight control system model during the powered approach phase of flight, an objective supported by the three TMP objectives. Cooper-Harper ratings were the primary evaluation metric for the flight tests, and were described in more detail in Chapter 2. The desired and adequate performance criteria were developed by the test team in conjunction with the model developer based on previous experience and expected design limitations. In addition to a CHR, a Pilot In-the-loop Oscillation rating was given by the pilot if a PIO was encountered during the approach and landing task. If a PIO was encountered, the pilot rated it according to the scale and provided comments on how objectionable the motion was and what effect it had on pilot opinion. The PIOR was used as another measure of performance in determining the handling qualities of the STAV model. A description of this scale was in Chapter 2.

The TIFS test plan began with the test methods and procedures conducted during LAMARS testing and refined them as necessary to make the flight testing flow more efficiently. The factorial design method used in LAMARS testing included four variables: pilot, offset, crosswind, and approach airspeed. This matrix was executed on LAMARS to verify predictions and narrowed down the actual TIFS flight test matrix. The TIFS flight test matrix also had four variables, but instead of approach airspeed as the fourth variable, in flight testing the final variable was the control system, either the baseline STAV model or the LAMARS optimized system. An approach airspeed of 185 knots was selected as optimal during LAMARS testing, and was no longer a variable.

The TIFS test plan also drew on the experiences of the Calspan pilots and engineers who had conducted other flight tests on TIFS. The TMP team looked at the process of using the Variable Stability System (VSS), and how to use it most effectively.

Previous flight test programs on TIFS indicated that the optimal time to switch to the VSS and transfer control to the evaluation pilot was on downwind. This procedure allowed pilots to gain an initial feel of the system while turning base and final, prior to conducting the approach and landing tasks. Discussions with Calspan also revealed that the maximum TIFS sortie duration was two hours. This drove the design of the test matrix to make the most efficient use of flight time by maximizing the number of approaches flown on each of the five planned flights.

The flight testing used TIFS-generated localizer and glideslope information to ensure repeatability in task performance between the different test pilots. This procedure was essential during the lateral-offset tasks, where a consistent offset point was required. This TIFS capability, which used the global positioning system, also allowed the test team to shift the desired touchdown point to 1,500 feet down the runway, a point on the runway which allowed better threshold clearance and enhanced test safety. The TIFS allowed the team to capture "touchdown" parameters at an actual altitude of 20 feet AGL, since landing gear airspeed restrictions limited testing to low approaches only. The landing distance criteria were measured from this "touchdown" point. These planned low approaches not only allowed the TIFS to conduct gear down approaches at speeds above maximum wheel touchdown speed, but allowed the test to model the pilot eye height of the STAV. When passing through the point on the touchdown plane, the performance parameters were recorded and displayed to the test team so that a Cooper-Harper evaluation could be completed.

In the weeks prior to flight testing, Calspan conducted one functional check flight and two calibration flights at the direction of the TMP team. The functional check flight

ensured that the TIFS aircraft would be ready for flight testing after several years spent in "flyable storage". The calibration flights integrated the STAV model with the VSS on TIFS, a task made more complex by the fact that the STAV model required that an additional computer be brought aboard the aircraft in order to run the flight tests properly. No modifications were made to the STAV model itself; all changes included just the top-level wrapper around the STAV model. The additional computer was VxWorks/PowerPC-based, which communicated to the model-following computer on TIFS via a standard 1553 bus. The real-time model was implemented on TIFS with the VxWorks program, which was an identical environment as Linux but included a gcc/g++ compiler. The source code and make-file which were originally compiled and checked in the Linux/Unix environment during previous testing therefore also worked in TIFS. In addition to the model calibration and integration, a TPS instructor ensured that all the various safety trips aboard the aircraft were operational prior to test team arrival. The pilot ran through the flight test cards to ensure that all maneuvers were safe and that all parameters were being recorded and displayed correctly. Finally, the pilot made sure that there were no significant time delays in the system that would impact testing, and that the TIFS model following performance was satisfactory. These checks of the time delay and model following were performed by running a predetermined set of test team Programmed Test Inputs (PTI) through the STAV model as implemented on TIFS and analyzing the response. These preparation flights were conducted the week prior to flight testing. The flight test cards are located in appendix C in figures C-10 through C-13, and have the same tasks as the previous test cards except for the vertical offset task, which was not accomplished during flight testing. The performance criteria are also the same

except for the landing zone, which was increased in size following inputs from operational bomber pilots, and the touchdown airspeed, which was removed.

Flight testing planned to fly one sortie the first day of flight test, and then two sorties each of the following two days. This allowed the test team to delay the flight tests if the weather was not sufficient or if there were maintenance or technical issues. It also allowed the data from a test flight to be analyzed immediately after landing, so that any lessons learned could be applied to the subsequent flights. Calspan pilots performed the initial taxi and take off, and flew the TIFS in between each run while the evaluation pilot (test team test pilot) was working with the test conductor to assign a Cooper-Harper rating. The test runs commenced once aircraft control had been transferred to the evaluation pilot. The evaluation pilot assumed control and performed the required task. Each evaluation pilot began the sequence of test points with a nominal or baseline precision approach and landing. To increase pilot workload, the crosswinds were increased to seven knots and the approach was repeated. The pilot then flew an offset approach with seven knots of crosswind. Each point was terminated by either a simulated touchdown, a safety pilot termination, or via the safety trips in the variable stability system onboard the TIFS.

When the aircraft was on the downwind leg, at approximately 1500 feet AGL, the evaluator pilot took control of the aircraft and performed a series of programmed test inputs and semi-closed-loop tasks. These inputs included steps and doublets in the pitch and yaw axes, as well as a step in the roll axis. The pilot recovered the aircraft to level flight after directed by the Calspan engineer in the back of the aircraft. The pilot then performed low gain capture tasks in pitch, roll, and heading. All maneuvers and

programmed test inputs were repeated with the spoilers completely retracted, and a set of pitch steps were accomplished while the spoilers were being retracted.

For all approaches, the TIFS generated a 2.5 degree glide slope that aimed at a point 750 feet long of the runway threshold. This point was chosen to provide sufficient safety clearance with a road that crossed perpendicular to the runway just prior to the overrun. This provided a ground distance of approximately 750 feet to flare before the planned touchdown point at 1,500 feet long of the runway threshold. The desired aim point and touchdown point are shown in figure 27.

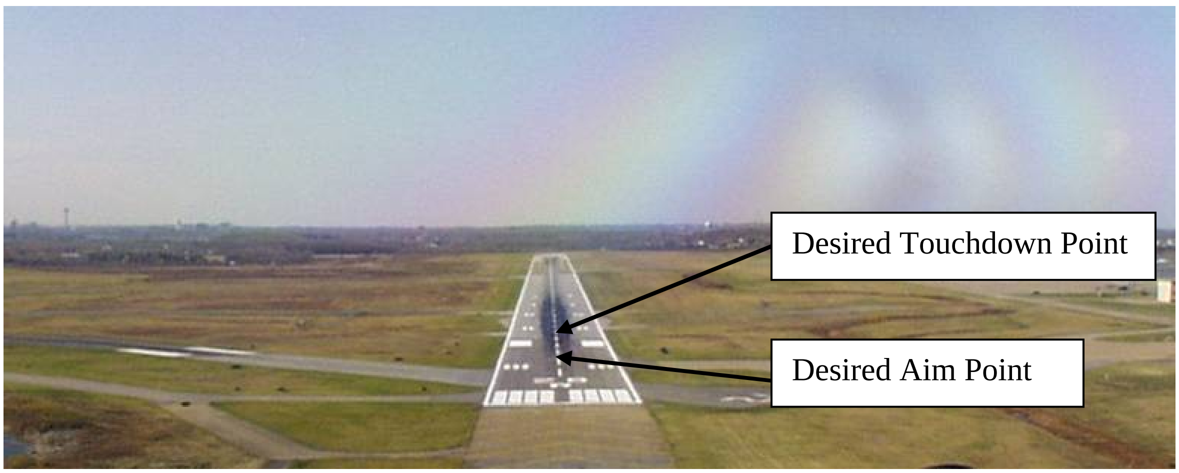

Figure 27 – Desired Aim Point and Touchdown Point

For all tasks requiring crosswinds, the TIFS side force generators were used to simulate a crosswind. The TIFS briefed capabilities stated that the side force generators could negate up to a fifteen knot actual crosswind, or add to the actual crosswinds to generate the effect of a fifteen knot crosswind. During flight testing, the test team found that when TIFS generated an effective crosswind greater than seven knots, the variable stability system was prone to nuisance systems trips with normal pilot inputs. These trips were due to the hinge forces generated by the side force controllers at a nominal approach

speed of 185 knots. Therefore, TIFS was used to generate or eliminate a maximum crosswind of seven knots.

For normal landing tasks, the 2.5 degree glide slope was aligned with the centerline. For the lateral offset tasks, the glide slope was offset by 200 feet from centerline, as shown in figure 28. It could be offset either right of left, based on the lateral correction direction dictated by the actual crosswinds. Any generated crosswinds required were from the direction opposite of the offset, which increased the task difficulty by forcing the pilot to correct into the crosswind. In the cockpit, the glideslope presentation to the pilot indicated on course when the pilot was lined up on the 200 foot lateral offset point. At 300 feet AGL, the test conductor called "maneuver", and the pilot aggressively maneuvered back to the centerline for the lateral offset tasks, in an effort to land at the desired touchdown point, which remained the same as the normal landing task. The approach airspeed was 185 knots in all cases.

Figure 28 – Lateral Offset Points

The data analysis plan used in reducing and analyzing the TIFS flight test data followed the same process used for the LAMARS data. While at the Calspan facility in Niagara Falls, copies were made of both the parametric data for each run as well as any

audio or video recordings. Each data run was given a number, so that it could be more easily organized after testing was complete. On each data run, a hard copy of a test card was used by the test conductor to record both pilot comments and initial performance parameters. During testing, test team members created excel spreadsheets to input Cooper-Harper ratings and performance data in order to get a real time quick-look of trend data on how the testing was proceeding. When the test team returned to Test Pilot School (TPS), the data were analyzed in order to determine whether each objective was met. The LAMARS data reduction set a baseline for the TIFS testing and prepared the Matlab, Excel, and other data reduction techniques that streamlined the TIFS data reduction effort.

At Calspan, a DVD of all the recorded in-flight parameters for each flight was made. TIFS also had a video camera in the evaluation cockpit to record an over the pilot's shoulder view of the testing. DVDs from each flight were gathered by the test team. During each flight, the test conductor again recorded pilot comments and initial parameters on a hard copy of each test card, which were marked with a run number. A run number for all the programmed test inputs and semi-closed-loop maneuvers was also recorded. After each flight, the pilot summarized their comments on the flight and wrote them in a daily flight test report. This daily flight test report included lessons learned in testing that would aid the subsequent pilots and test conductors in their data flights. Cooper-Harper ratings and performance information were again inputted into an Excel spreadsheet, to provide a quick-look on trend data. This process continued between each flight. After flight testing was completed, a brief with Calspan was conducted to summarize the quick-look results and gather any preliminary lessons learned.

After returning to TPS, the flight test engineers took the data and reduced it according to each test team objective. For the first objective, Cooper-Harper ratings of the baseline system were summarized on a histogram according to both task and individual pilot. For the second objective, Cooper-Harper ratings for both the baseline and optimized system were compared according to both task and pilot. Pilot performance using both of the systems was also compared. Another comparison between the baseline and optimized system was made by plotting pilot aggressiveness and duty factor. For the third objective, the model following capability of the TIFS was displayed. This included flight conditions with both calm conditions and with turbulence. An additional method used to investigate the STAV handling qualities measured pilot aggressiveness and duty factor when conducting the different approach and landing tasks. Pilot aggressiveness was determined by measuring the speed of the inceptor movements, while duty factor was a measure of the percentage of time the pilot was "in-the-loop", moving the inceptor. This method was used post-flight to compare the pilot's perception of workload and predictability during the tasks with the actual inceptor movements.

3.7 Summary

This chapter explained in detail the various test methods and procedures used during the course of this thesis. It first focused on the scope and assumptions of this thesis. It then covered the overall general test methodology, including the initial test procedures developed using the previous LAMARS testing by the NGC. The methods and procedures used during each of the three different test sections were then outlined, including a data analysis plan for the results of each section. As the testing progressed, the methods and procedures were modified not only to fit the new test environment, but

also to improve the flow and management of data. The lessons learned from a previous section's testing were applied to the next and so on; resulting in testing that became more refined and efficient as it progressed. This evolution in testing applied not only to the conduct of the test, but also to the data reduction at the conclusion of testing.

4.0 Results and Analysis

4.1 Overview

This chapter contains the results and analysis of all testing conducted throughout this thesis, and is divided into the three main test sections: Infinity Cube Simulator (ICS) testing, Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS) testing, and Total In-Flight Simulator (TIFS) testing. For the ICS testing, it summarizes the pool of pilots by number and classification. It breaks down the results of each test section first by aircraft, then by overall handling qualities (HQ) rating and data precision, and finally by HQ rating and data precision according to pilot classification. For the LAMARS and TIFS testing, it looks at results of the baseline and LAMARS optimized models, as well as the comparison between the two. The results include pilot performance and CHR for all three test sections and pilot workload vs. aggressiveness for the LAMARS and TIFS testing. Each section discusses: if the pilot ratings differed according to classification; ways to improve the test results; and underlying issues that hindered the tests or proved to be poor assumptions.

4.2 Infinity Cube Simulator Testing

Testing in the Infinity Cube Simulator took place from 16-18 October, 2006. Testing followed the procedures and methods explained in the previous chapter. After submitting a request to the pilot population at the Air Force Institute of Technology, nineteen pilots were available to participate in the tests. These nineteen pilots had varying backgrounds and experience levels. This pool of pilots averaged over 1,570 hours of flight time each in thirteen different fixed wing and rotary wing aircraft. The following table 5 shows the pilot pool for the ICS testing, including total number and

average flight time of each pilot group. Table G-1 in appendix G contains individual pilot information.

Table 5 – Infinity Cube Simulator Pilot Pool

Pilot Group	USAF	Navy	Civilian	Fighter	Heavy	Non-Test	Test
Number	12	6	1	10	9	16	3
Avg Time (Hrs)	1647	1342	2000	1542	1611	1495	2000

The pilots conducted 228 total approaches and landings, including 57 for practice and 171 for data. Each pilot flew twelve approaches, three for practice and nine for data. This further broke down into one practice and three data runs each for the T-38 model, the STAV model at 175 knots, and the STAV model at 195 knots. Four tasks were accomplished during testing, a precision approach and a normal landing on the first run, a lateral offset landing on the second run, and a vertical offset landing on the third run. The test cards in appendix C provide more detail on each task, and the approach and landing performance criteria are displayed in tables 6 and 7.

Table 6 – Infinity Cube Simulator Approach Criteria

Precision Approach	Desired	Adequate
Deviation from approach airspeed	±5 knots	±10 knots
Deviation from glideslope	± 0.5 dot	± 1.0 dot
Deviation from localizer	± 0.5 dot	± 1.0 dot

Table 7 – Infinity Cube Simulator Landing Criteria

Precision/ Offset Landings	Desired	Adequate
Landing zone	±25 ft laterally ±500 ft longitudinally	±50 ft laterally ±1000 ft longitudinally
Deviation from touchdown airspeed	± 5 knots	± 10 knots
Max bank angle below 50 feet	± 5 degrees	± 7 degrees
Max touchdown sink rate	6 ft/sec	10 ft/sec
Deviation from runway heading at touchdown	± 2 degrees	± 4 degrees

4.2.1 T-38

The T-38 model was flown first by every pilot. After completing each data run and analyzing their performance and workload, the pilot would give a longitudinal and lateral CHR for each task. The average CHR for the T-38 tasks was a three, corresponding to level one HQ. The original testing on the T-38 was completed before the CHR scale came into existence, so there is no exact historical comparison. However, the USAF policy on aircraft HQ states that for normal mission tasks, the HQ should be level one. The T-38 has been flying operationally in the USAF for the past forty-six years, and although it can be tricky to land, the HQ are generally accepted as level one for approach and landing. Therefore, the level one rating given by the ICS test pilots corresponded well with real-world operational experience. There were no statistically significant CHR or performance differences between any of the pilot groups for the T-38 testing. The largest differences in longitudinal and lateral CHR were between the Air Force and Navy pilots (figure 29), while the greatest difference in performance achieved was between fighter and heavy pilots (figure 30). The use of a baseline aircraft was vital to ensure that the pilots were correctly using the CHR scale. It served as a basis by which the results of a group of non-test pilots could be compared to historical data.

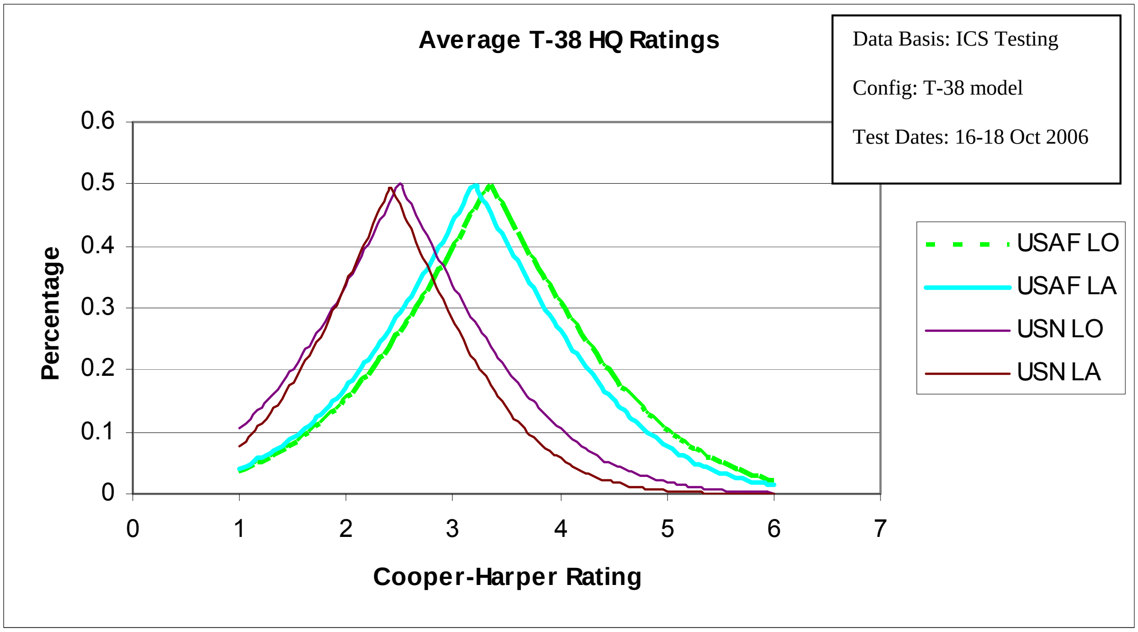

Figure 29 – Air Force vs. Navy T-38 CHR

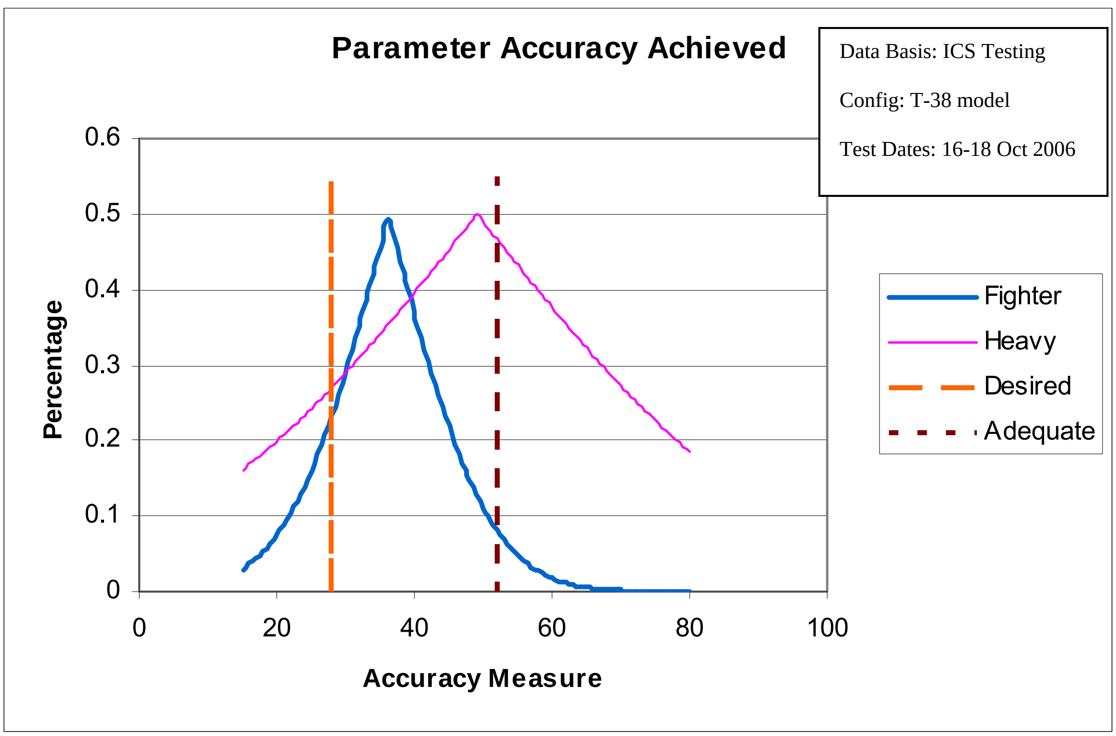

Figure 30 – Fighter vs. Heavy T-38 Performance

The performance achieved by each pilot was termed parameter accuracy, and was calculated by weighting each performance criterion equally and then adding the total deviations from ideal touchdown parameters (on speed, heart of the landing zone, no bank or heading deviations, zero sink rate). All plots were formed by calculating the mean and standard deviation of each pilot group, and then taking a normal distribution of the data. A summary of the CHR for each task and model is located in table A-1 in appendix A.

4.2.2 STAV (ICS)

The version 1 STAV model was tested next, and included the 30% spoiler bias mentioned previously. Half of the pilots flew the test tasks at 175 knots approach speed first, and then at 195 knots. The other half flew in the reverse order. The ratings of both of these groups were analyzed to determine how much the ratings improved from the first set of approaches to the second set of approaches. The average CHR improved 0.65 for the 175 to 195 group, and got worse by 0.21 for the 195 to 175 group. These values were used to determine the mean learning effect, which was applied to the data from both groups to cancel out any perceived ratings improvement caused solely by learning (i.e. the pilots performing better as they fly the STAV more). This allowed the 175 knot and 195 knot models to be compared by all pilots equally, indeterminate of test run order. Overall, the average CHR was 5.2 for the 175 knot STAV and 4.9 for the 195 knot STAV, a statistically insignificant ratings difference.

The mean longitudinal and lateral learning effects were 0.43 and 0.62, which meant that the CHR of whatever a pilot flew second improved by that amount. After applying these learning effects to the data, the effects themselves were analyzed to

determine if one group of pilots learned at a different rate than another. As expected, individual pilots learned at different rates. When the learning rates of different pilot groups were studied, some interesting trends broke out. Although the statistical difference between pilot groups was lessened after taking variation among the nineteen different pilots into account, the mean learning effects of each group depicted some disparity. Figure 31 shows the mean longitudinal learning effects of each pilot group. The largest differences in learning effect were in the longitudinal realm, where both Air Force vs. Navy pilots and Fighter vs. Heavy pilots showed opposite learning trends. The Air Force and Fighter pilot groups tended to rank better whatever STAV approach speed they tested second. The Navy and Heavy pilot groups tended to rank whatever STAV approach speed they tested first as slightly better.

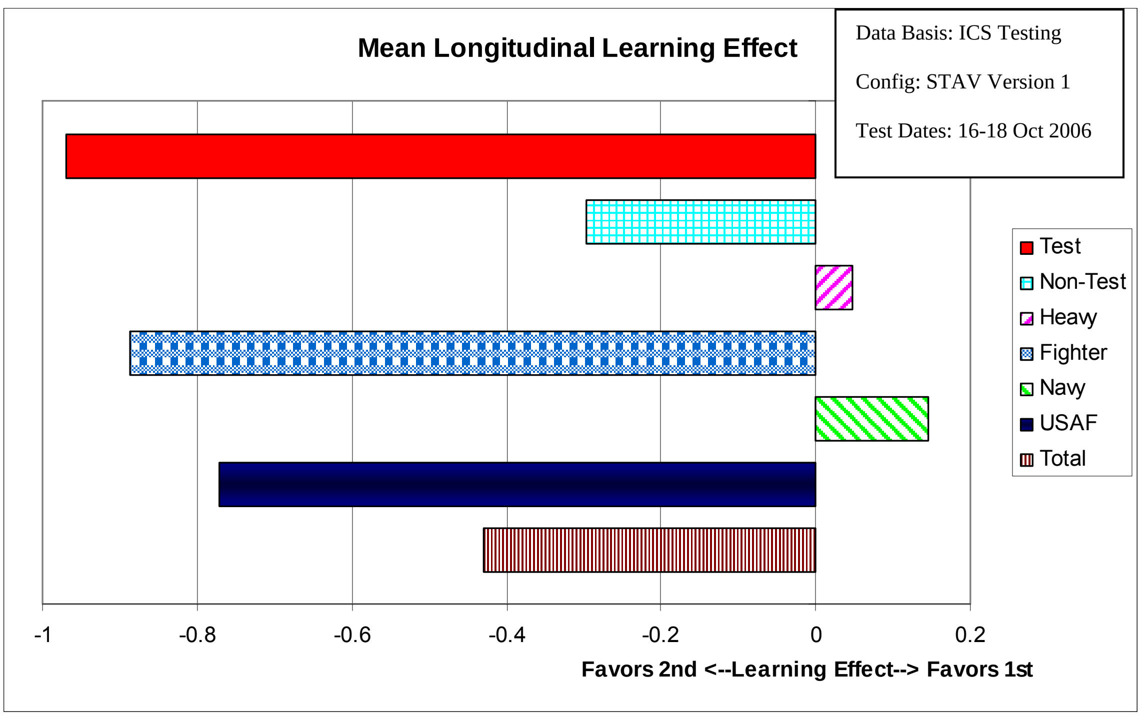

Figure 31 – Mean Longitudinal Learning Effect in ICS Testing

In the lateral realm, the learning effect differences were not as significant. All pilot groups tended to rank better whatever STAV approach speed they tested second. Figure 32 shows the mean lateral learning effects of each pilot group.

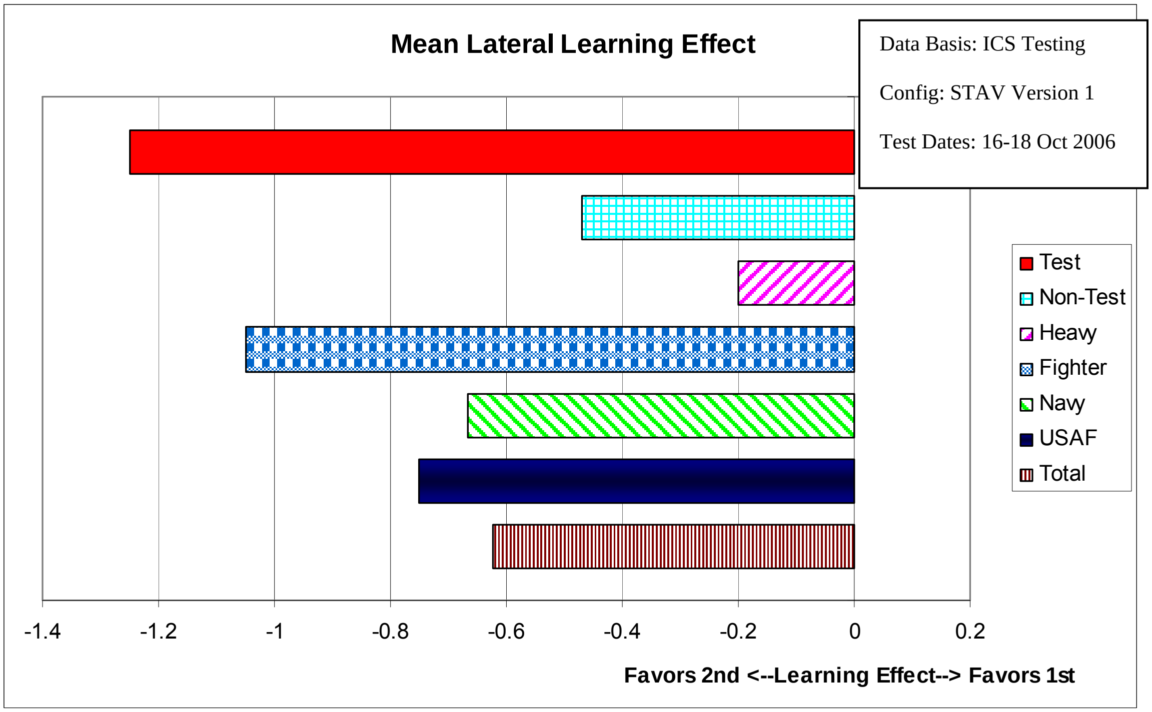

Figure 32 – Mean Lateral Learning Effect in ICS Testing

The overall results for the STAV model were that every task at both approach speeds was rated level two. This compared closely with the results from the initial NGC LAMARS testing, where every task at both approach speeds was also rated level two, except for the vertical offset landing at 195 knots, which was rated level one. Table 8 shows the average CHR and standard deviation for each task for both the initial NGC LAMARS testing and the ICS testing. Even though the test pilot sample size increased by a factor greater than six, the standard deviation for each task remained the same order of magnitude.

Table 8 – Initial NGC LAMARS Testing vs. ICS Testing CHR

Task	Initial Mean	Initial σ	ICS Mean	ICS σ
Approach – 175	4.67	0.58	4.26	1.71
Approach – 195	4.50	0.50	4.07	1.40
Land – 175	4.50	0.50	5.59	1.79
Land - 195	4.33	1.15	5.00	1.74
Lateral Offset – 175	4.50	0.71	5.50	1.81
Lateral Offset – 195	4.67	1.53	5.45	1.59
Vertical Offset – 175	4.33	1.15	5.28	1.83
Vertical Offset – 195	3.33	1.33	5.26	1.64

The aerodynamic characteristics of the version 1 STAV model were used to calculate the predicted HQ. This resulted in predicted HQ of level one or two. As shown before, the HQ were rated level two during ICS testing. Table 9 shows the predicted HQ based off of the aerodynamic characteristics of the version 1 STAV model.

Table 9 – STAV Aerodynamic Characteristic Predicted HQ

Characteristic	STAV value	Predicted HQ level
ζ_{sp}	1.85 - 1.92	2
ω_{sp}	1.4 - 2.7	1
ζ_p	0 – 0.13	1 / 2
CAP ($\omega_{sp}^2/(n/\alpha)$)	0.48 – 1.02	N/A
n/α	4.09 – 7.16	1
ω_{sp} vs. n/α	N/A	1
CAP vs. ζ_{sp}	N/A	2
$\omega_{sp}T_{\theta 2}$ vs. ζ_{sp}	N/A	2

There were no statistically significant CHR or performance differences between any of the pilot groups for the 195 knots STAV testing. The largest difference in CHR was between Non-test and Test pilots (figure 33).

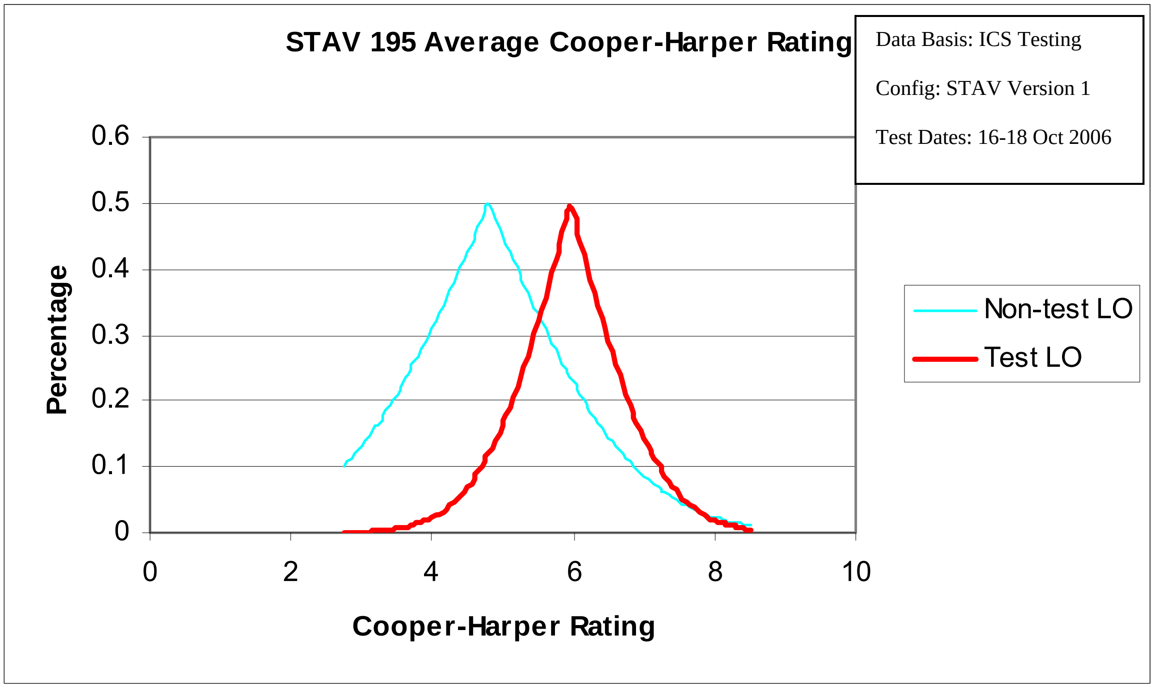

Figure 33 – Non-test vs. Test STAV 195 Longitudinal CHR

For the 175 knot STAV model, there were statistically significant differences between Air Force vs. Navy pilots and Non-Test vs. Test pilots. More than 68% of the Navy pilots rated the 175 knot STAV model better than the 195 knot model, and the reverse corresponded to Air Force Pilot ratings. Figure 34 shows the longitudinal CHR differences between Air Force and Navy pilots. These differences indicated a Navy pilot preference for the slower speed approaches, a fact that matched well with current naval approach operations, which are conducted at lower airspeeds on the back side of the power curve.

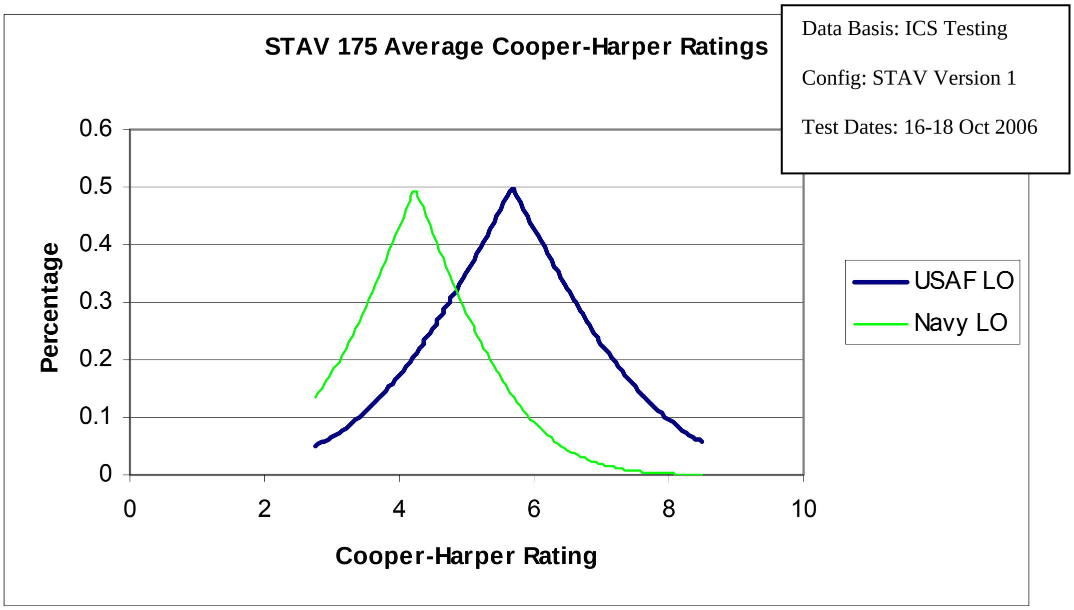

Figure 34 – Air Force vs. Navy STAV 175 Longitudinal CHR

When test and non-test pilot longitudinal and lateral CHR were compared for the 175 knot STAV model, the differences were even greater. Over 74 % of non-test pilots rated the 175 knot STAV model better than the test pilots for longitudinal CHR, and over 78% for lateral CHR. The following figures 35 and 36 clearly depict these statistically significant differences in both longitudinal and lateral CHR. The differences between these two groups are most likely the result of improper use of the CHR scale than a preference for a certain approach speed. Test pilots are more apt to rate an aircraft properly based on workload and performance. Although briefed on proper use of the CHR rating scale, non-test pilots showed a potential tendency to rate the aircraft better than what the workload and performance called for, basing any lack of performance more on piloting skill than on aircraft deficiencies. All of the test pilots were also Air Force pilots, another potential influence on the ratings differences.

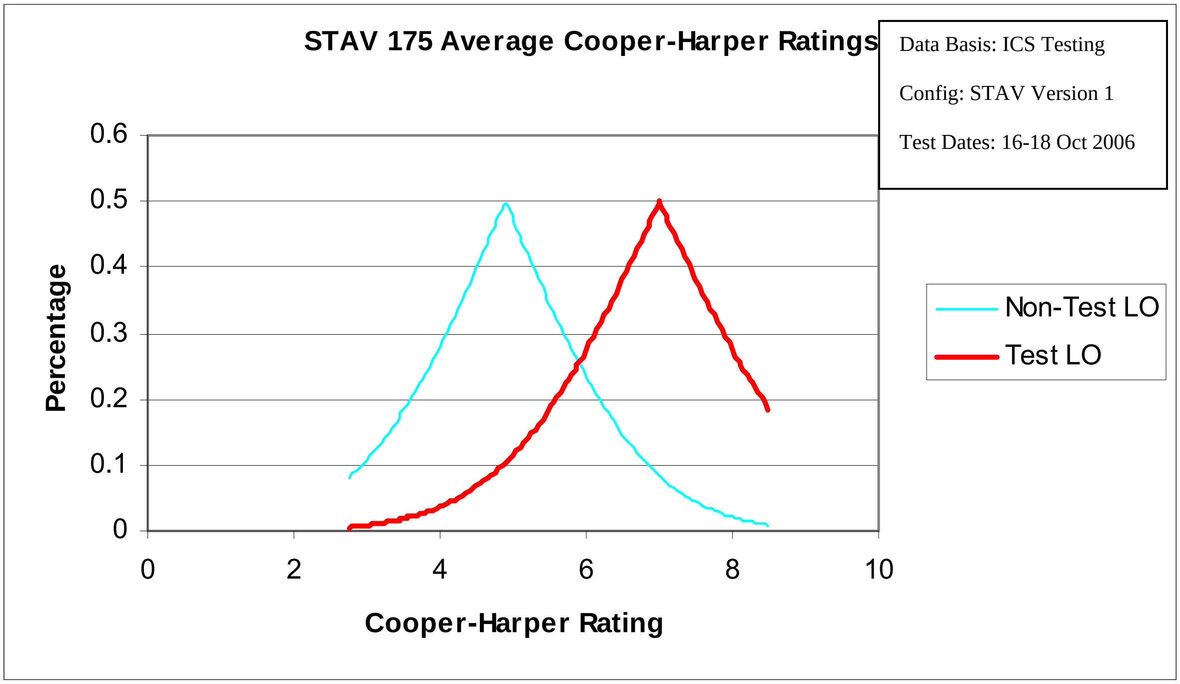

Figure 35 – Non-test vs. Test STAV 175 Longitudinal CHR

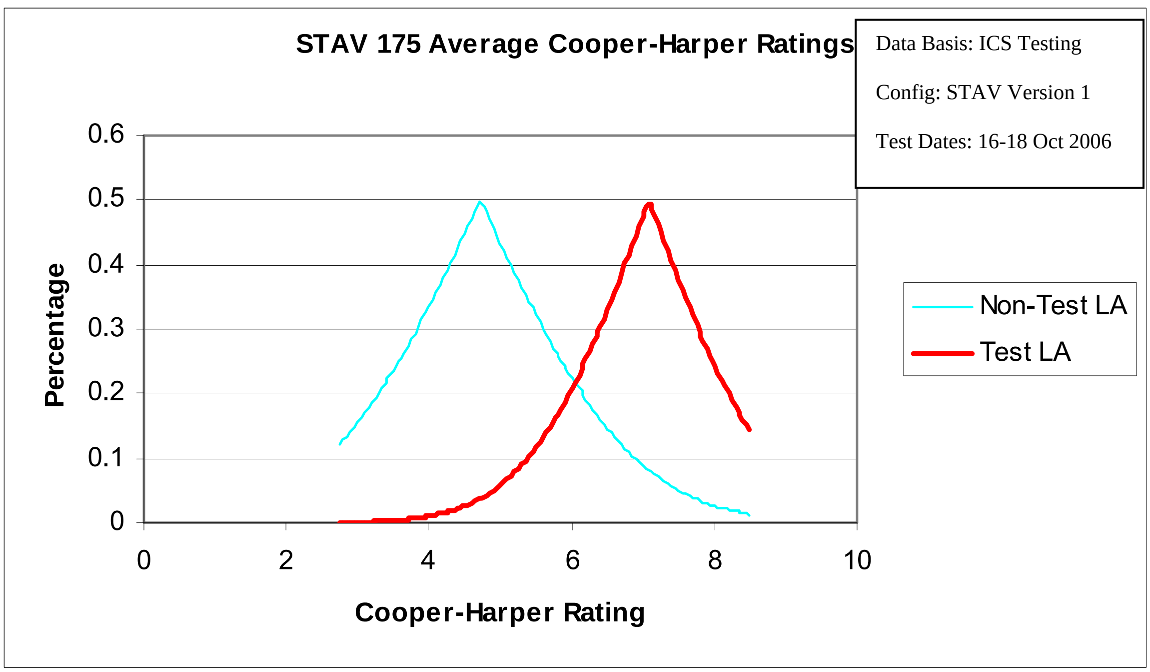

Figure 36 – Non-test vs. Test STAV 175 Lateral CHR

As mentioned previously, a mean learning effect was applied to the data so that the 175 and 195 knot STAV tasks could be isolated independent of test run order. This

allowed the data to be reduced to determine if any pilot group preferred a certain approach speed over another. The largest difference in preferred approach speed was between the Air Force and Navy pilots. Of all the Air Force pilots, 68% preferred the 195 knot STAV approach speed, while 62% of the Navy pilots preferred the 175 knot approach speed. These results agreed with the previous STAV 175 knot CHR differences shown earlier in this chapter. Figure 37 shows the preference differences between Air Force and Navy pilots. The piloting techniques employed by the pilots of different services showed that previous experience had an impact on HQ rating.

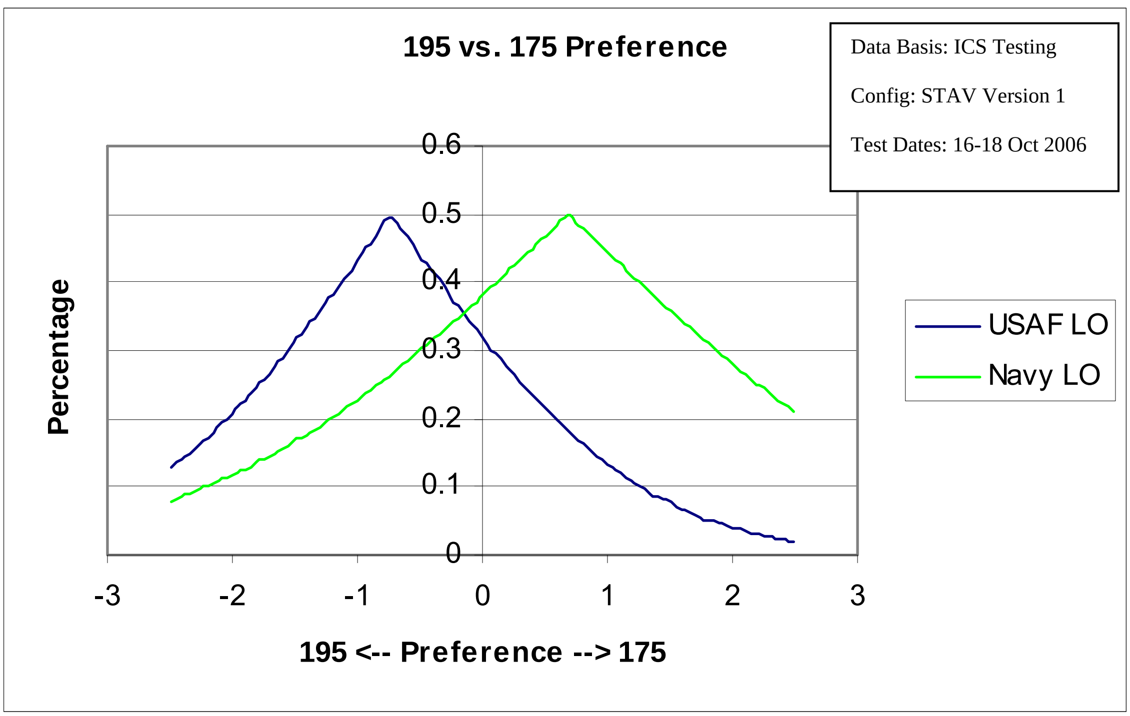

Figure 37 – Air Force vs. Navy Preferred Approach Speed

STAV parameter accuracy (performance) of each pilot was calculated in the same manner as the T-38 parameter accuracy, by weighting each performance criterion equally and then adding the total deviations from ideal touchdown parameters (on speed, heart of the landing zone, no bank or heading deviations, zero sink rate). The only two groups to

show a statistically significant difference in performance achieved were the Fighter and Heavy pilots, and this difference is depicted in figure 38.

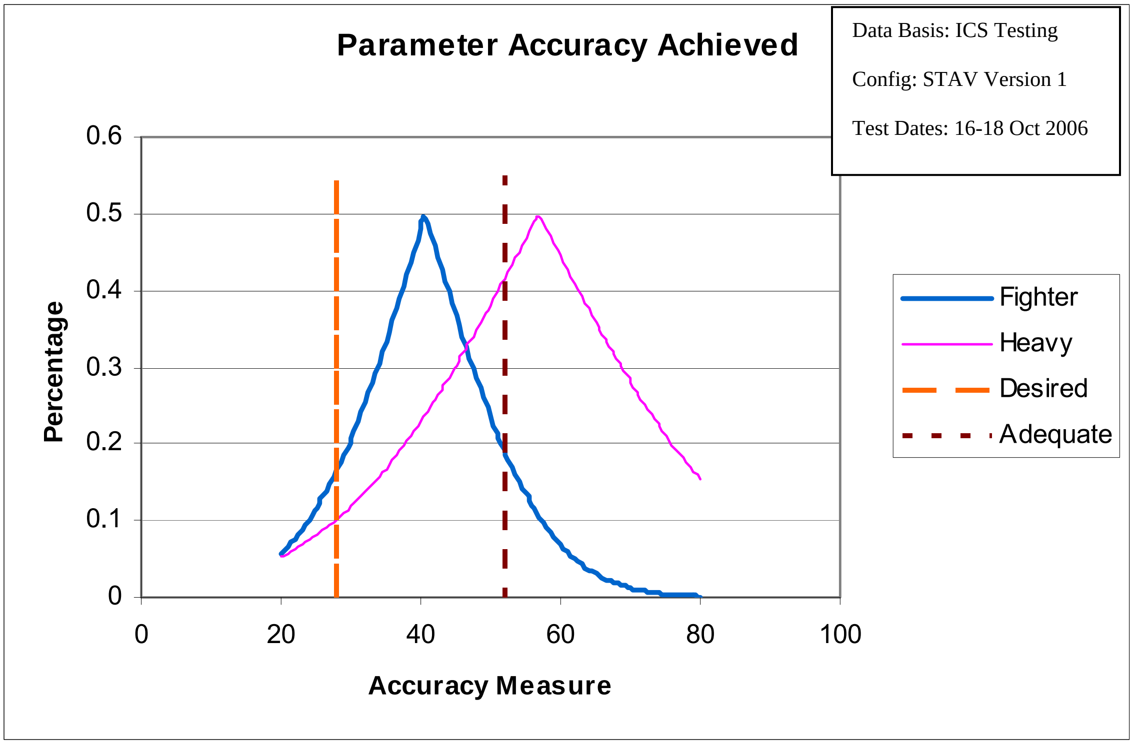

Figure 38 – Fighter vs. Heavy Parameter Accuracy Achieved

About 68% of the Fighter pilots achieved more precise touchdown parameters than Heavy pilots. These results make sense, because fighter pilots in general have to fly with greater precision than heavy pilots in order to accomplish an operational mission. These results did not speak to the skill of a certain pilot group, or say that one group of pilots was better than another; it merely highlighted the fact that the type of flying normally conducted by each pilot group had an impact on task performance.

Overall, the pilot accuracy correlated well with the pilot rating, where the pilots who performed the best generally gave the best CHR. This was not always the case, since pilot workload was also taken into account when compiling a CHR, but it was the general trend. This analysis was made to ensure that pilots who were performing poorly

were not giving erroneously good CHR. Figure 39 shows a plot of pilot CHR and parameter accuracy according to each individual. The parameter accuracy was scaled to better fit the plot, as the purpose was to convey the accuracy level in relation to the other pilots; the actual individual accuracy values were not important.

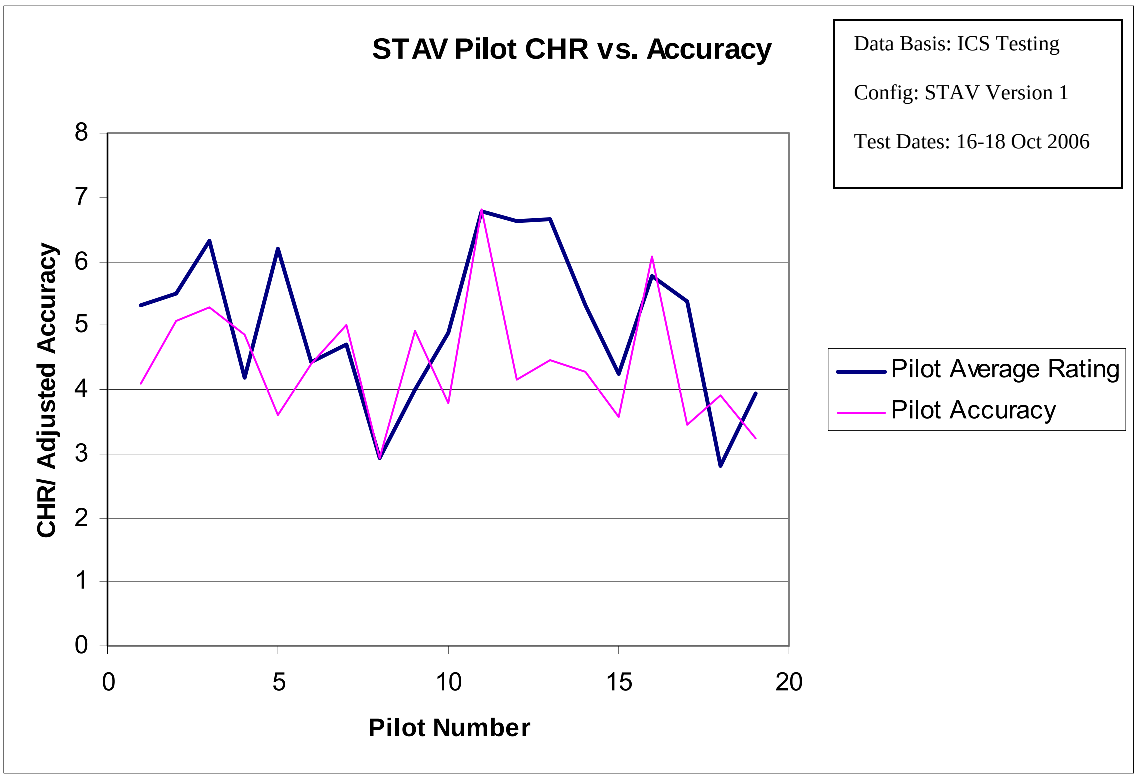

Figure 39 – STAV Pilot CHR vs. Accuracy

After analyzing the results, some areas for improvement and possible underlying impacts on testing were postulated. The use of both the heads up display (HUD) and side-stick caused some initial consternation with pilots not used flying with either, but this impact was lessened by letting the pilots have a practice approach in each model. Some of the pilots complained that the simulator brightness hindered the visual corrections during the offset landing tasks and during the flare. Having motion along with brighter visuals would improve the quality of the simulation. The STAV model

could not be trimmed, a factor which impacted pilot performance and CHR. The lack of ground effect also led to a tendency to balloon in the flare. These impacts would be mitigated with an increased fidelity STAV model that was trimmable and accounted for ground effect and gear modeling. The touchdown airspeed criterion of 160 knots may have also had a negative impact on CHR, and should be increased for subsequent testing. There should only be one CHR assigned per task, as it was difficult to divide lateral and longitudinal performance and workload and assign a CHR for each.

The displayed HQ of the STAV model illustrated the need for a thorough safety plan prior to any flight testing. The speeds and offset tasks need to be evaluated to ensure that all safety of flight issues are met, and an altitude buffer between the ground and the aircraft would provide an extra margin of safety should some of the more disagreeable handling qualities surface. Pilots should be allowed to conduct more approaches, so that any learning effects can take place prior to data collection. An expanded test profile should include not only approach and landing tasks, but also tasks throughout the expected mission envelope. This testing should include synthetic vision testing, as some sort of synthetic vision will be necessary to safely operate and land the STAV. A HUD should be used in further testing, as it reduced pilot workload, especially during the flare. Further testing should focus on using test pilots. These pilots do not require similar backgrounds; they should just be test pilots who are familiar with conducting a handling qualities evaluation. Further testing should be accomplished on some type of aircraft with a variable stability system. This would allow the tester to look at current and future STAV models, as well as the ability to revert to another aircraft should the need arise when in close proximity to the ground.

4.3 LAMARS Testing

Prior to testing in LAMARS, each HAVE STAV pilot flew the different test tasks in a TPS T-38 so that they could become familiar with them and validate that they were operationally valid and safe. Each pilot flew with the TMP staff test pilot in the back seat, so that they fly and rate the tasks while getting instruction on CHR. The correction altitude and magnitude of the offset were varied during the lateral offset landings until safe and operationally valid task parameters were decided upon. The same process was repeated for the vertical offset tasks. The tasks were flown at full flap and no flap conditions to simulate the effects of different pilot sight pictures (the cockpit view a pilot has when landing) during the correction maneuver and the flare. After flying 25 approaches on three sorties, the parameters were set at a correction altitude of 300 feet above ground level (AGL) for both offset tasks and offset magnitudes of 200 feet for the lateral task and a half-dot (half-degree) above glideslope for the vertical task. These values were added to the LAMARS test cards and lessons learned about pacing and test conduct were explained to the entire HAVE STAV test team prior to leaving TPS.

LAMARS testing of the version 2 STAV model was conducted on 6-7 August 2007 at Wright-Patterson Air Force Base. Four pilots completed 160 different approaches for data during sixteen hours of testing. Individual information regarding these four pilots is found in table G-2 of appendix G. Three flight test engineers flew approximately forty minutes of simulation each to prepare for TIFS flight testing. Table B-1 in appendix B contains the entire test matrix used in LAMARS testing. LAMARS was selected over the ICS so that a direct comparison of test data could be made with a second round of LAMARS testing conducted by the Northrop Grumman Corporation

(NGC) in November 2006. The model used in this testing was also the version 2 STAV model, which now included ground effect and gear modeling, as well as an angle of attack (alpha) compensation technique used to reduce pilot workload when maneuvering. The test team wanted a high-fidelity full-motion simulation that replicated as closely as possible the motions anticipated on TIFS test sorties. A HUD was not used during LAMARS testing because the TIFS cockpit did not have one. A center inceptor location was used instead of a side stick in order to better replicate the TIFS cockpit. The main objective was to identify an optimized flight control system, feel system, or technique to flight test in the TIFS in addition to the baseline STAV model. Testing was conducted in three phases, the first of which investigated the flying qualities of the baseline STAV model and compared the alpha-command (angle of attack), gamma-command (flight path), and q-command (pitch rate) control systems. All tasks were again designed to land the aircraft 1,000 feet down the runway on centerline. The performance criteria were also the same as ICS testing except for the desired and adequate sink rate criteria, which were decreased to account for the STAV landing gear structural capabilities. The precision and offset landing performance criteria are shown in table 10.

Table 10 – LAMARS Landing Criteria

Precision/ Offset Landings	Desired	Adequate
Landing zone	±25 ft laterally ±500 ft longitudinally	±50 ft laterally ±1000 ft longitudinally
Deviation from touchdown airspeed	± 5 knots	± 10 knots
Max bank angle below 50 feet	± 5 degrees	± 7 degrees
Max touchdown sink rate	4 ft/sec	6 ft/sec
Deviation from runway heading at touchdown	± 2 degrees	± 4 degrees

4.3.1 Baseline STAV Model

Results from the first phase of testing closely matched the results of previous NGC LAMARS control system testing. All three HAVE STAV pilots agreed that even though it required improvement, the alpha-command control system should be tested further in TIFS. The gamma controller was slightly less intuitive to the pilot, but obtained comparable results to the alpha controller during low workload tasks. If no large lateral corrections were required (due to high crosswinds or lateral offset), and workload remained low, the gamma controller provided performance results comparable to or slightly better than the alpha controller. However, in cases where large lateral corrections were required, the aircraft motions and control inputs were unnatural to the pilots. If actual instrument conditions were present, the pilots would easily become spatially disoriented. The pitch rate controller provided the biggest challenge for all of the pilots and was the most disorienting to use. It was difficult to predict the response of the aircraft to a longitudinal input, making it hard to maintain the glideslope and flare the aircraft. Each pilot developed a technique for accomplishing the flare during the first phase, after which the pilots decided on a standardized flare technique that involved altitude calls by the test conductor at AGL altitudes of 100, 50, and 20 feet and a timed power reduction when passing through 20 feet. At the end of this first phase of testing, the team collectively decided to conduct all further testing and control system modifications with the alpha-command control system.

During the first phase of testing, all pilots noted that the flare was the most difficult part of a landing task. Handling qualities during the approach (above 300 feet AGL) were not problematic. In fact, pilots commented that maintaining the appropriate

glideslope and alignment with the runway were not challenging, and that the HQ should be considered satisfactory. However, once close to the ground (below 300 feet AGL), the longitudinal inputs required to maneuver and flare the aircraft were difficult to control. The flare typically required a tradeoff between satisfying either the landing distance or the sink rate evaluation criteria. When the pilot focused on achieving the desired sink rate criterion, the typical result was a landing distance of 1500 to 2000 feet long of the desired touchdown point. When the pilot focused on meeting the desired landing distance criterion, the typical result was a hard touchdown with sink rate between six and ten feet per second. The first phase of testing began with the first pilot flying approaches at 175 and 195 knots. The second pilot flew at 185 and 195 knots, and the third pilot at 175 and 185 knots. The first pilot flew again at 185 knots, and agreed with the other pilots that 185 knots was the best approach speed for STAV. This approach speed was then used in all subsequent testing.

Before any test runs were completed, a flying qualities check was made on each control system. This check was accomplished via a series of pilot inputs that included steps and doublets. The aircraft characteristics, including short period frequency and damping and time delay, were measured and compared to the baseline model characteristics. The comparison was made by both the HAVE STAV test team and an NGC engineer in charge of STAV flight controls. The flying qualities of the STAV as implemented on LAMARS were the same as those exhibited by the baseline STAV model during previous testing.

4.3.2 Model Optimization

During the second phase of testing, the longitudinal inceptor force gradient was increased just prior to entering the flare. This was done to limit the undesired pitching motions and pilot tendency to over-control during the flare. Using the procedures outlined in the LAMARS testing section of chapter 3, the pilots came up with optimized values for both the force gradient and the altitude of the gradient change. The optimal gradient was determined to be five times the baseline gradient, or approximately 13.5 pounds of force per inch of inceptor deflection. This gradient was a compromise between the two fighter test pilots who preferred lighter inceptor forces (four times the baseline gradient) and the heavy test pilot who favored heavier inceptor forces (seven times the baseline gradient). The selected gradient reduced the tendency to over-control during the flare, and increased the pilot's ability to make an acceptable landing even when initially off parameters (i.e. steep flight path angle or high airspeed). The optimal height above ground for the gradient change was 100 feet AGL. Below 100 feet AGL, the gradient change had a negative impact on the flare. Pilots pulled aft on the inceptor to begin the flare, and during this pull the force gradient suddenly increased, which resulted in an undesirable increase in workload. Above 100 feet AGL, the gradient change interfered with pilot's inputs during a lateral or vertical correction, and caused an increase in workload.

After the increased longitudinal inceptor gradient testing finished, the effects of spoiler retraction during the flare were investigated. As in both the ICS and previous NGC LAMARS testing, the spoilers were initially set to a 30% bias in order to provide better speed stability and control. The spoiler retraction minimized the throttle change

required to maintain airspeed during the flare. This led to a more natural pitching moment during the flare, and reduced the landing gear sink rate generated by an aft pull on the inceptor. Pilots noted that the aircraft response to inceptor inputs during the flare was more predictable when accompanied by the spoiler retraction. An automatic spoiler retraction height of 30 feet AGL was decided upon by the pilots as optimal. The altitude of the retraction depended heavily on a pilot's flare technique. If the pilot attempted to approach the landing zone with a higher than normal airspeed and slow down during the flare, then the spoilers would completely retract well before touchdown. If the pilot attempted to approach the landing zone with slower than normal speed and attempt to make a spot landing, then touchdown would occur prior to complete spoiler retraction. The optimal altitude selected allowed for complete spoiler retraction just as a nominal touchdown occurred. If touchdown did not occur within a few seconds after complete spoiler retraction, then the aircraft would tend to "float" down the runway in ground effect. This floating tendency sometimes caused the aft part of the aircraft to strike the runway due to dangerously low airspeeds or high attitudes. The inceptor force gradients of both the baseline and LAMARS optimized STAV control systems are shown in table 11.

Table 11 – STAV Control Systems

Control System	Breakout Forces (Pounds)	Friction Forces (Pounds)	Force Gradient (Pounds/Inch)	Longitudinal Travel (Inches)	Alternate Control Technique
Baseline	1	1	2.6	3.2 forward / 4.2 aft	N/A
LAMARS Optimized	1	1	13.5 @ 100' AGL	3.2 forward / 4.2 aft	Spoilers retracted @ 30 ft AGL

4.3.3 Baseline/ LAMARS Optimized Model Comparison (LAMARS)

The flare HQ showed improvement when coupling the spoiler retraction with the increased longitudinal inceptor force gradient. When using the optimized control system, the handling qualities were regularly acceptable or better during the landing tasks and were usually only unacceptable during high crosswind or lateral offset landing tasks. These results were an improvement over the normally unacceptable baseline STAV model HQ. Tables 12 and 13 show the Cooper-Harper ratings for the baseline and optimized systems, as well as the performance achieved for both systems. While the optimized system still had a good portion of inadequate landings and therefore unacceptable HQ, it displayed a marked improvement over the baseline STAV model.

Table 12 – LAMARS Baseline vs. Optimized CHR

CHR	3	4	5	6	7	8
Baseline	0	1	13	1	22	3
Optimized	4	1	6	1	8	0

Table 13 – LAMARS Baseline vs. Optimized Performance Achieved

	Desired (Total %)	Adequate (Total %)	Inadequate (Total %)
Baseline	1 (2.5)	14(35)	25 (62.5)
Optimized	5 (25)	7 (35)	8 (40)

The percentage of inadequate performance landings decreased by 36% from the baseline, while the percentage of landings with desired performance increased by a factor of ten. Also of note was the near lack of CHR of 6, defined as “adequate performance requires extensive pilot compensation.” Pilots were generally not working hard enough to give a CHR of 6. This was due in large part to the lack of perceived sink rate by the pilots. The pilots would think that they were about to make a desired or adequate landing, but after touchdown would realize that the sink rate was too high. This nearly

imperceptible sink rate prevented the pilots from working harder (extensive pilot compensation) to achieve adequate landing criteria, and therefore they either gave a CHR of 5 (adequate performance required considerable pilot compensation) or a CHR of 7 (adequate performance not attainable with maximum tolerable pilot compensation). The CHR of 7 were always based off of inadequate performance, not workload. The three CHR of 8 were assigned because the pilot encountered some undesirable pitching motions and considered them an incipient Pilot In-the-Loop Oscillation (PIO). These motions were not encountered with the optimized control system.

After the three test team pilots had flown both the baseline and optimized systems, the TPS staff pilot flew both systems. After analyzing the performance achieved and workload required, the pilot agreed with the test team that the handling qualities of the optimized system were indeed better. The predictability and repeatability of the optimized system in the flare, while still not acceptable, were a marked improvement over the baseline.

When flying the baseline model, the pilot would approach the landing and begin to flare the aircraft. Instead of arresting the sink rate, the vertical velocity would increase and the pilot would either impact the ground at a high sink rate or over-control and cause the aircraft to balloon. The optimized system showed no tendency to increase in sink rate as the inceptor was pulled aft. The pilot would approach the landing, pull aft on the inceptor to begin the flare, and the sink rate would gradually decrease until touchdown. The sink rates encountered during a normal approach and landing for both the baseline and optimized control systems are shown in figure 40. This plot shows the vertical velocity of the aircraft (sink rate) in the moments prior to touchdown, not the aircraft

flight path. The plot therefore depicts a hard landing with the baseline system, not a balloon.

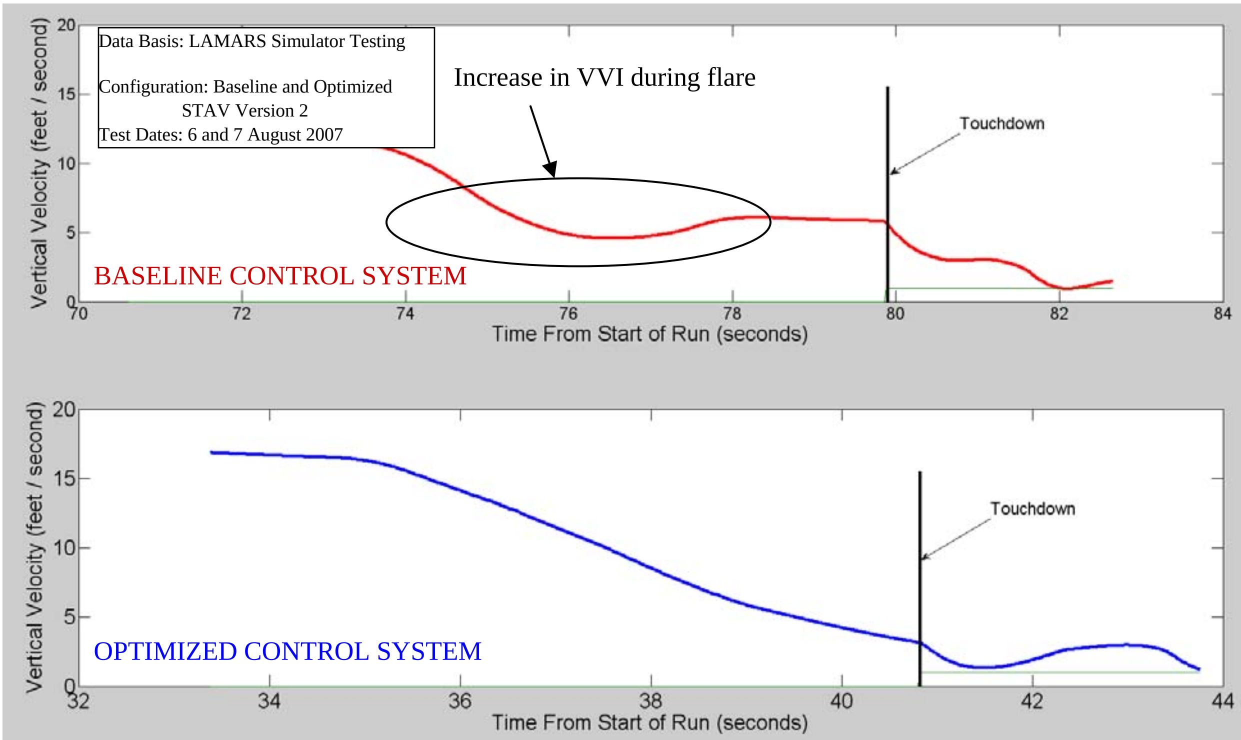

Figure 40 – Sink Rate of Baseline vs. Optimized Systems

Another method was created to determine differences between the baseline and optimized systems after TIFS testing was completed. This method was then applied to the LAMARS test data. The inceptor velocity was measured as a function of time, and used as a metric for pilot aggressiveness. The percentage of time that the pilot was moving the inceptor over a given period was measured, and used as a metric for duty factor. These two metrics were then plotted against one another to determine if aggressiveness and duty factor differed between the systems and/or influenced pilot opinion on performance and predictability. Figure 41 depicts pilot aggressiveness and duty factor for both the baseline and optimized systems. This figure quantifies the physical workload as a two-dimensional combination of aggressiveness and duty cycle

that serves as a time-domain analogous representation of the frequency-domain concept of "frequency content." Large, abrupt, and frequent inceptor motions are plotted in the upper right corner and are analogous to "high pilot gain." Conversely, small, smooth, infrequent inceptor motions are plotted in the lower left corner and correspond to "low pilot gain."

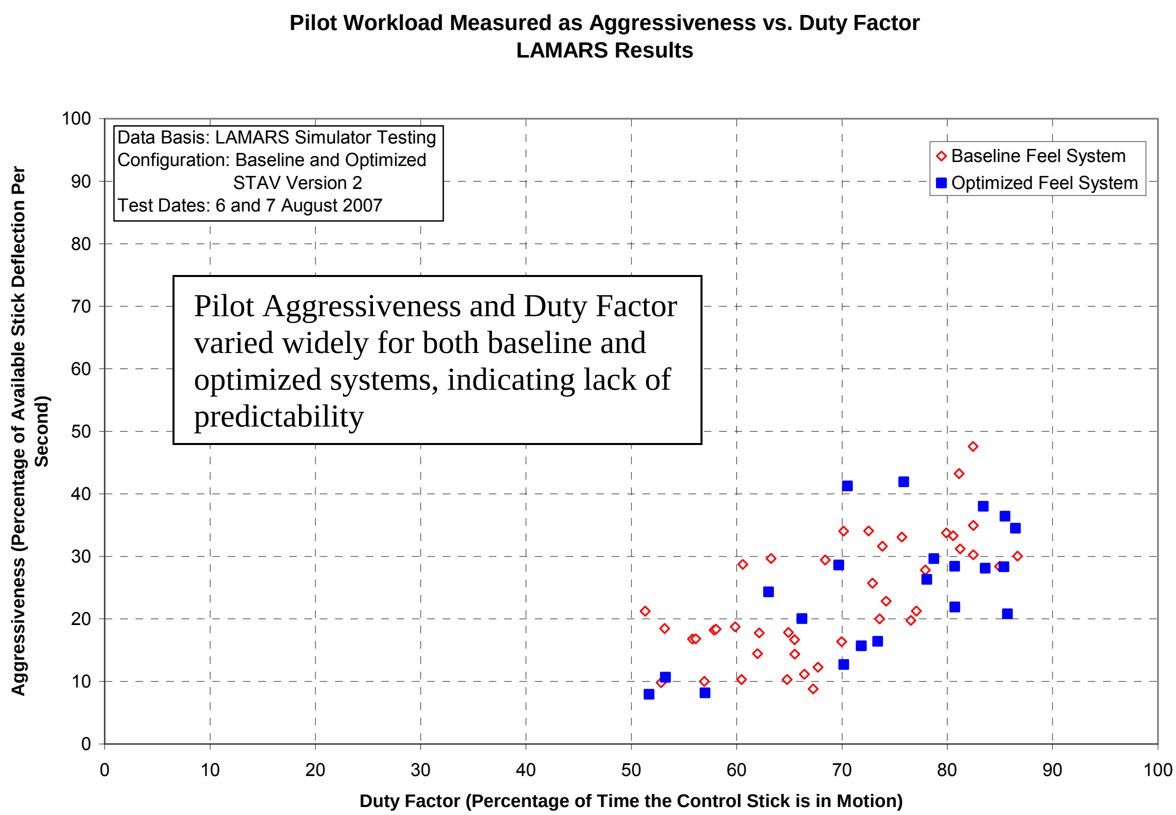

Figure 41 – LAMARS Pilot Aggressiveness vs. Duty Factor

This analysis showed no significant differences between the baseline and optimized systems. Even though the optimized system resulted in better HQ than the baseline, both systems displayed a wide range of achieved performance, and showed a certain lack of predictability. Consequently, both systems varied widely in overall aggressiveness and duty factor. Although the data were somewhat spread, it did portray a general relationship between pilot aggressiveness and duty factor for both systems. As

the duty factor decreased the aggressiveness tended to decrease, and as the duty factor increased there was a corresponding increase in aggressiveness.

After the optimized system had been completely developed, the baseline system was retested to ensure that improved handling qualities were not attributed to practice alone. The same tendencies to over-control during the flare were observed when the baseline STAV model was retested. Task performance in the flare was again unpredictable, and resulted in almost the same number of adequate and inadequate landings. Table 14 shows the original baseline performance achieved on the first day of testing compared to the final baseline performance achieved on the second day of testing.

Table 14 – LAMARS Baseline Performance Achieved

	Desired (Total %)	Adequate (Total %)	Inadequate (Total %)
Day 1 Baseline	1 (4.5)	7 (31.8)	14 (63.6)
Day 2 Baseline	0 (0)	7 (38.9)	11 (61.1)

After analyzing the LAMARS results, some areas for improvement and possible underlying impacts on testing were proposed. The selection of the 185 knot approach allowed the pilots time to acclimate to a single approach speed, and reduced the number of test variables. This allowed a more direct comparison to be made between the baseline and optimized system in the limited test time available. During the landing tasks, the pilots noted that there was a parameter (performance) trade-off when attempting to make a desired or adequate landing. Either the landing distance criterion or the sink rate criterion could generally be met, but not both. This relationship should be investigated further in TIFS. Both the lateral offset task and crosswinds increased the pilot gain to an appropriate level while remaining operationally valid. The vertical offset task did not drive up the gain as much as desired, and should be left out during TIFS testing. The lateral offsets increased the pilot gain the most during testing. The background of each

pilot did not have a significant impact on the perceived HQ ratings. The heavy pilot found that the technique used to flare heavy aircraft was better suited in the STAV than the flare technique initially employed by the fighter pilots, and this technique became the accepted test technique. The preferred force gradient was the only other pilot-specific factor that arose during testing, and this was settled via compromise between the pilots.

In addition to yielding several interesting results, the LAMARS testing also provided some lessons learned for future testing. Better visuals in LAMARS would increase the realism of the simulation. The displays were not bright enough to pick up on the very subtle visual cues available to the pilots during the flare. A blended inceptor gradient change would result in a less disruptive impact on the pilot during the approach. While the pilots liked the higher gradient and the timing of the change, they did not like how abrupt it was. The use of altitude calls and a standardized power pull reduced pilot workload and increased consistency, and should be employed during flight testing. Practice approaches allowed the pilot to become more familiar with flying the tasks, and should be used to the maximum extent possible. More approaches would also allow more thorough testing of each system. The touchdown zone criteria should be resized to better reflect an operationally acceptable landing area. Current large bomber aircraft routinely land up to 2000 feet long of there intended touchdown point. A crosscheck of the flying qualities of the STAV model as implemented on TIFS should be made to again ensure model fidelity during testing.

Overall, the simulator had a higher fidelity than the ICS with its visuals and motion, and was a good preparation for the flight tests. It allowed the team to test the baseline system, develop an optimized system, and refine the test methodology to make

the flight testing more efficient. The exposure of the pilots and engineers to the baseline STAV model limited the potential for surprises during flight test. This preparation proved to be critical because of the limited flight test time available to conduct a thorough handling qualities evaluation. Turbulence was not implemented on LAMARS, and in future testing this should be looked at to determine how the model responds to wind gusts or turbulence prior to flight testing. This lack of turbulence meant that the pilots were largely out of the loop prior to maneuvering the aircraft through a task, and did not get used to the inceptor feel until below 300 feet AGL. This prevented the pilots from getting used to the lighter inceptor forces prior to the gradient change, and precluded them from perceiving the control harmony mismatch (an unwanted discord between longitudinal and lateral inceptor forces) discovered during flight testing. Finally, the limited runs did not allow a thorough exploration of the gamma-command controller. The benefits of this controller should be further studied, especially during low gain tasks.

4.4 TIFS Flight Testing

Flight testing of the version 2 STAV model on the TIFS aircraft was conducted from 10-13 September 2007 in the airborne traffic pattern at Niagara Falls International Airport. A total of six flights and ten hours were flown during testing, as summarized in table 15. This included sixty-seven different approaches for data. A detailed synopsis of the test points flown on TIFS is presented in table D-1 in appendix D. A summary of the pilots who flew on TIFS is found in table G-3 in appendix G. The flight testing objectives were: to determine the powered approach handling qualities of the baseline STAV model, to compare the LAMARS optimized control system to the baseline STAV

control system, and to determine the flying qualities for the TIFS simulation of the STAV flight control system. All figures in this section and appendix E are from the HAVE STAV Technical Information Memorandum (Speares, et al., 2007).

Before the first flight, the test team conducted ground training on TIFS to familiarize the pilots with the displays, Variable Stability System (VSS), and egress procedures of the aircraft. This allowed the team to practice test team procedures on the ground, which preserved actual flight time for the test tasks. The test team went through the process of engaging the VSS and transferring aircraft control from one cockpit to another, which made the flight testing more efficient.

Table 15 – Summary of Test Flights

Flight	Duration	Description	Test Crew
1	2.0	10 Sep 07 1410L / TIFS flight 2498	Speares, Neff, Porter
2	1.0	11 Sep 07 0940L / TIFS flight 2499	Domsalla, Cook, Gray
3	2.0	12 Sep 07 1010L / TIFS flight 2500	Quashnock, Porter, Domsalla
4	2.0	13 Sep 07 0740L / TIFS flight 2501	Quashnock, Neff, Speares
5	2.0	13 Sep 07 1030L / TIFS flight 2502	Domsalla, Cook, Quashnock
6	1.0	13 Sep 07 1510L / TIFS flight 2503	Speares, Cook, Gray

Each test team pilot flew three test sorties, and each flight test engineer flew either two or three sorties. While the test pilot and test conductor flew in the forward evaluation cockpit, the third member of the test team would fly in the aft engineering compartment, and relay real-time task performance achieved to the forward evaluation cockpit so that CHR could be assigned. On the first test flight, the rudder feedback to the VSS initially caused the system to go offline. After adjusting this feedback, the VSS worked properly and the flight continued. The VSS continued to work properly over the remaining test flights, apart from a small number of nuisance trips encountered as testing progressed. The second test flight was cut short by weather, which prevented testing the

multiple sorties planned for days two and three of the flight test schedule. Flight three was the **2500th** TIFS test sortie, and on the fourth day of testing three flights were conducted, allowing the test team to complete the flight test schedule. The ability to triple turn TIFS on a single test day was a testament to the capabilities of both the aircraft and the Calspan personnel responsible for TIFS operations.

. The TIFS performance criteria were similar to those used in LAMARS testing. The two differences were the longitudinal dimension changes of the desired and adequate landing area, and the removal of the touchdown airspeed criteria. While an on-speed touchdown was desirable, it was not critical to the landing HQ unless it deviated grossly from nominal. Table 16 lists the pilot performance criteria used during flight testing. In addition to these criteria, touchdown airspeed had to be greater than 165 knots and touchdown pitch attitude had to be less than fifteen degrees. These restrictions were put in place to prevent a simulated runway strike with the aft part of the aircraft.

Table 16 – TIFS Performance Criteria

Precision Landing and Lateral Offset Landing	Desired	Adequate
Landing zone	±25 ft laterally +1000 / -500 ft longitudinally	±50 ft laterally +1500 / -750 ft longitudinally
Maximum bank angle at touchdown	± 5 degrees	± 7 degrees
Maximum touchdown sink rate	4 ft/sec	6 ft/sec
Deviation from runway heading at touchdown	± 2 degrees	± 4 degrees

4.4.1 Baseline STAV Model (TIFS)

The first test objective was to determine the powered approach handling qualities of the baseline STAV model. For the tests completed, the baseline STAV handling qualities were predominantly unacceptable. A total of thirty-three approaches were flown with the baseline feel system, with a methodical buildup in workload.

Normal approaches were flown first, followed by normal approaches with crosswind. Lateral offsets were then accomplished, followed by lateral offsets with crosswind. Cooper-Harper ratings given by all pilots totaled one Level 1 rating, fifteen Level 2 ratings, and seventeen Level 3 ratings. Pilot In-the-Loop Oscillation ratings were assigned twice, each for non-divergent oscillatory motions. Figure 42 summarizes the CHR of both the baseline and optimized systems. Additional histograms of CHR assigned during testing are shown in appendix E, figures E-1 through E-5. For all approach types, the driving factor for the unacceptable handling qualities was inadequate task performance. For most baseline feel system approaches, the pilot workload and compensation were both determined to be acceptable.

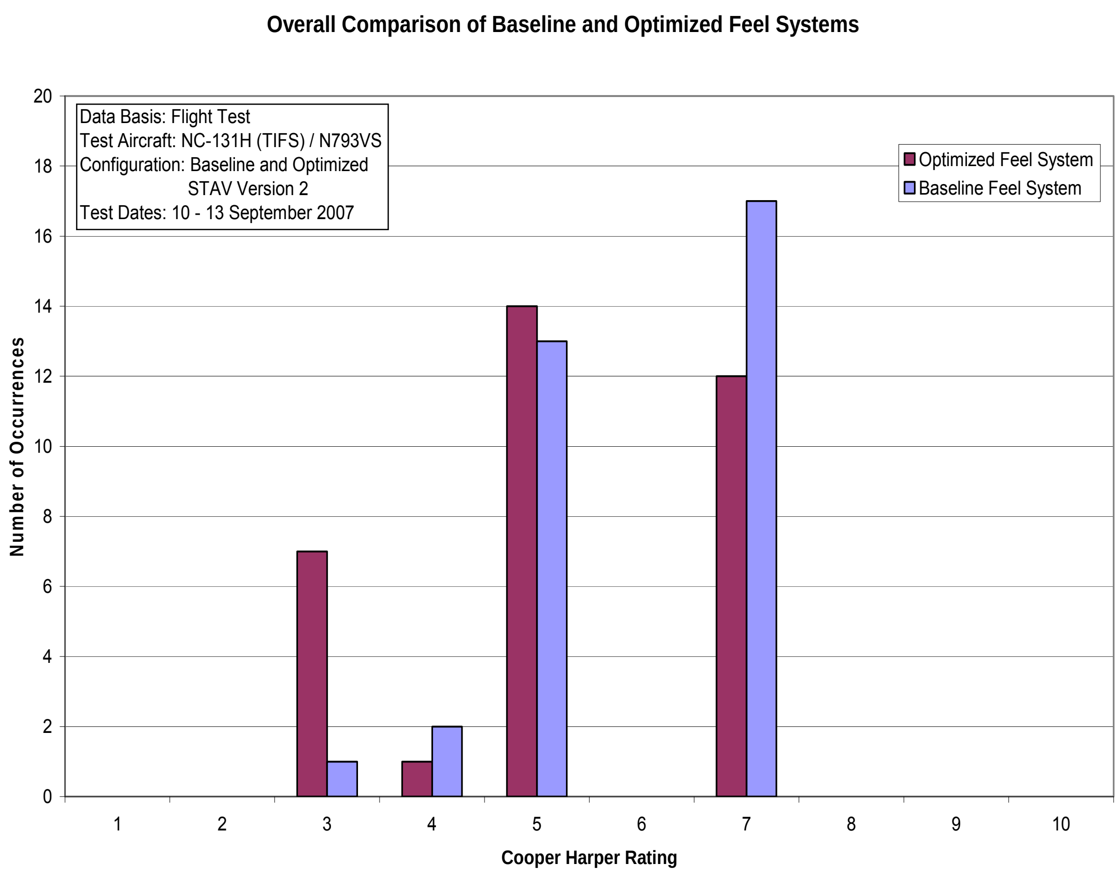

Figure 42 – TIFS Baseline and Optimized CHR Summary

The purpose of the different approach types was to create tasks that would increase pilot workload (while maintaining the same performance criteria) in order to uncover key HQ characteristics. The sequential workload buildup used by the TMP team in LAMARS testing was again employed in TIFS using the task order already described: normal approach, normal approach with crosswind, lateral offset, and lateral offset with crosswind. In LAMARS, the escalation in workload with each task was evident in both pilot comments and performance. The actual workload buildup experienced in TIFS testing was different. As expected, the normal precision approach still required the lowest workload and the combined offset and crosswind task remained the highest workload, presumably due to the complex combination of control inputs required. However, the corrections and inceptor movements required to fly an approach with crosswinds resulted in a higher pilot workload than the corrections and movements required to fly a lateral offset approach.

While the lateral offset task required a lower workload than expected, landing performance achieved during these landings remained worse than the performance achieved with the normal landings. Of nine lateral offset landings, seven failed to meet adequate criteria and none achieved desired criteria. However, there was no single reason for the performance inadequacy. Three of the approaches failed to meet adequate criteria for touchdown distance (long), three for sink rate, and four for excessively high pitch attitude. Two of these approaches had multiple performance inadequacies.

At nominal NC-131H approach speeds, the TIFS aircraft had the capability to generate the effects of up to a fifteen knot crosswind or negate an actual fifteen knot steady state crosswind using side force generators on the wings. However, the high hinge

forces present on the side force generators at the HAVE STAV approach speed of 185 knots meant that the actual crosswind capability was limited to only a seven-knot generation or reduction of crosswind. For most of the baseline approaches (19 of 33), conditions included light to moderate turbulence and variable crosswinds both with and without gusts. In these conditions, removing crosswinds was difficult for the TIFS to manage without tripping the VSS by exceeding control surface limits. As a result, many of the "zero-crosswind" approaches were flown without crosswind simulation, which meant flying in actual crosswinds ranging from zero to seven knots. These conditions were perceived by the pilots to have a higher workload than either the lateral offset or crosswind tasks themselves. Unscheduled and unpredictable disturbances caused by turbulence or wind gusts required the pilots to continually correct the aircraft's attitude all the way to simulated touchdown, which meant a large increase in pilot workload.

The designed tasks as well as the environmental conditions increased pilot gain to levels appropriate for the purposes of the flight testing. Neither the tasks nor the conditions were assessed to be unrealistic for an operational bomber mission. The weather conditions in particular revealed the sometimes subtle handling qualities characteristics of the model during approach and landing. Although the crosswind tasks in TIFS increased pilot gain, the turbulence encountered during flight test drove up the pilot gain even more.

Sink rate at touchdown was the critical performance parameter responsible for the Level 2 and Level 3 HQ ratings during the approach and landing tasks. Even though the longitudinal landing zone criteria were increased, there was still a trade-off between the landing zone and sink rate parameters. When the desired sink rate was assiduously

pursued, this most often resulted in only an adequate or inadequate longitudinal touchdown point (typically long). The pilots remarked that they lacked sufficient cues to estimate aircraft sink rate. Due to the touchdown eye height of the notional STAV (and the corresponding simulated touchdown point), peripheral vision did not provide the pilots a "ground rush" cue to arrest the sink rate. The lack of a HUD meant that all instrumented cues required the pilot to be "heads down" during the most critical part of the landing, the flare. The test conductor provided some sink rate feedback by calling altitude remaining until touchdown at 100 feet, 50 feet, and every 10 feet thereafter. This allowed the pilots' eyes to remain outside. While these audio cues helped the pilots, they were insufficient. Other cues that involved more than just current aircraft parameters were needed but not available. Combining the current aircraft parameters with some sort of predictive guidance information from a flight director or predictive flight path marker would increase the STAV flight predictability, particularly during flare and landing. This predictive guidance would provide the pilot information on what the aircraft parameters would be in the near term future if no inputs were made to the throttles or inceptor. A flight director could guide pilot inputs in order to achieve desired landing performance. Neither a flight director nor any types of predictive guidance were used during testing. Without these additional cues, the landing became a mechanical exercise where flare height and power reduction were determined strictly by altitude. The aircraft characteristics and overall time delay made it difficult to predictably flare and land the aircraft in this manner.

The most objectionable flight control characteristic during a landing with the baseline STAV model was pitch sensitivity. The inceptor force gradient was 2.6 pounds

per inch. Full aft inceptor deflection was 4.2 inches and required a force of just 10.92 pounds. The light control forces required during the flare decreased predictability and increased pilot workload. The baseline inceptor gains during approach and landing resulted in objectionable inceptor sensitivity and increased duty cycle and aggressiveness. Testing also revealed that there was a time delay in flight path response on the order of one second, which reduced the predictability of pitch inputs and resulted in open-loop, methodical pilot compensation during approach and landing. These techniques included power reductions and flare initiation at specific altitudes, and were characterized by step or impulse inputs that waited for the aircraft to respond between inputs.

While the primary portion of the pilot comments concerned HQ in the pitch axis, some interesting commentary involved lateral-directional issues. Turbulence cause a roll sensitivity in the aircraft. Lateral accelerations were noted simultaneously with aircraft roll rates when the pilot commanded a roll, a characteristic that was subtle but not objectionable. When a roll rate was induced by outside disturbances such as turbulence or wind gusts, lateral accelerations were more apparent, though still not objectionable. Other notable commentary involved the alpha compensation during turns. An upward pitching moment was experienced when rolling into a turn and a downward pitching moment when rolling out of a turn. These moments required the pilot to impart an unnatural push when rolling into a turn and an unnatural pull when rolling out of a turn.

4.4.2 Baseline/ LAMARS Optimized Model Comparison (TIFS)

The second test objective was to compare the LAMARS optimized control system to the baseline STAV control system. The optimized system was identical to the baseline system until 100 feet AGL, when the longitudinal force gradient was increased

to five times the baseline value over a one-second span. At 30 feet AGL, the spoilers were automatically retracted and the aircraft was landed. The properties of the two systems were previously detailed in table 10. A total of thirty-four approaches were flown with the optimized system, again with a methodical buildup in workload. The comparison of the LAMARS optimized control system with the baseline STAV control system showed that the optimized system had improved handling qualities over the baseline system. The number of landings which achieved desired performance nearly tripled, while the number of inadequate landings decreased by 30%. This relationship is portrayed in the previous figure 42 and in figures E-1 through E-5 in appendix E. While there was an increase in performance over the baseline system, the optimized system still had almost twice as many unacceptable landings as satisfactory landings. These results indicated that the optimized system, while better than the baseline system, still had major deficiencies requiring improvement.

The TIFS testing showed a complete lack of CHR of 6, defined as “adequate performance requires extensive pilot compensation.” This phenomenon was exhibited first in LAMARS, and surfaced again in flight testing. Pilots were generally not working hard enough to give a CHR of 6. This was due mostly to the lack of perceived sink rate by the pilots, where they would think that they were about to make a desired or adequate landing, but after touchdown would realize that the sink rate was too high. This unpredictable sink rate again prevented the pilots from working harder (extensive pilot compensation) to achieve adequate landing criteria, and therefore they either gave a CHR of 5 (adequate performance required considerable pilot compensation) or a CHR of 7

(adequate performance not attainable with maximum tolerable pilot compensation). The CHR of 7 were once again always based off of inadequate performance, not workload.

The comparison of the optimized system with the baseline system was accomplished by alternating between the baseline and optimized systems during each test flight, as shown in appendix D. This test methodology helped to control some of the different influences on testing, including: weather, turbulence, pilot proficiency, and variations in procedure between flight test engineers. Each pilot had approximately three flight hours for the comparison. For the first hour, each pilot began with a buildup in workload flying the baseline system. For the second hour, each pilot repeated the tasks with the optimized system. For the third hour, only zero-crosswind, straight-in approaches were flown, nominally alternating between two runs with the baseline system and two runs with the optimized system. Natural crosswinds were flown if it was determined that the TIFS was unable to reliably model crosswinds at the 185 knot approach speed.

The optimized system resulted in an aircraft that was much less sensitive in pitch, and was more capable of achieving a repeatable and predictable flare, even when entry conditions to the flare were varied. The optimized system required different flare timing than the baseline system. All three pilots, on their first approach with the optimized system, flared high. This difference in timing highlighted the fact that the entire STAV approach, regardless of the control system, was very reliant on open-loop flying technique rather than closed-loop flying down to landing. After an input was commanded, the pilot waited for the aircraft to respond to see what correction would be required. The correction for leveling-off too high required an unnaturally strong push,

instead of a simple relaxation of longitudinal pull. This push was more noticeable with the increased inceptor force of the optimized system and correspondingly increased the workload. This increase in workload led to at least one landing that achieved desired performance but was deemed to require improvement because of the moderate pilot workload required. Even with a sometimes increased workload, pilot performance tended to improve with experience, as shown by the decrease of inadequate landings presented in figure 43.

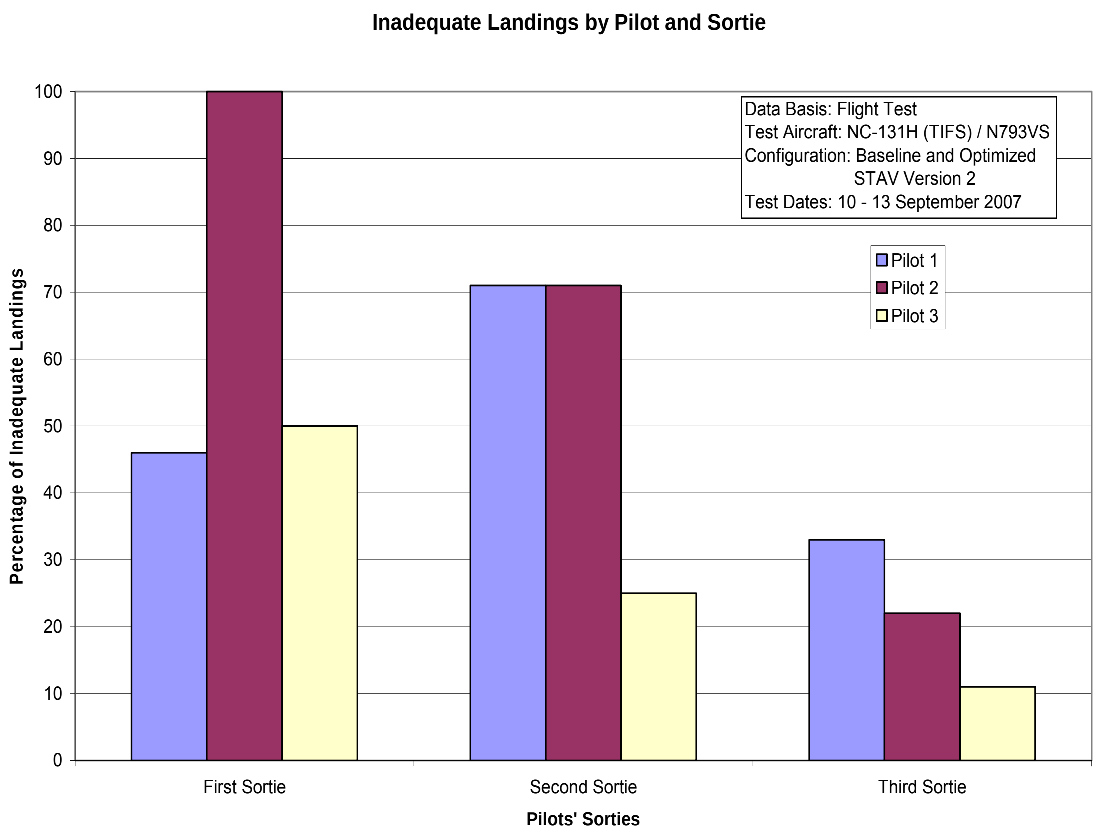

Figure 43 – Inadequate Landings by Pilot and Sortie

Weather, especially turbulence and wind gusts, had a significant impact on the perceived handling qualities of each system. In smooth air, the optimized system was more conducive to Level 1 HQ. The baseline system was more sensitive, requiring extensive compensation that led to Level 2 landings even when desired performance was

achieved. In turbulence, the optimized system made it easier to compensate for glideslope deviations during the flare. However, both systems still required extensive compensation during the entire approach in the form of small, frequent inputs. The optimized system did not display the same sink rate reduction in the flare during flight test as it did in LAMARS. This was most likely a result of the nominal turbulence encountered on short final. In the absence of gusts, the optimized system could still be flown to Level 1 landings, even in moderate turbulence. The inceptor forces of the baseline system, however, were so light that moderate turbulence would cause the inertia of the pilot's hand to move the control, which added to the already considerable compensation required.

Figure 44 shows the difference in physical workload required by the two systems, and again quantifies the physical workload as a combination of aggressiveness and duty cycle that characterizes a frequency-domain concept with a time-domain representation.

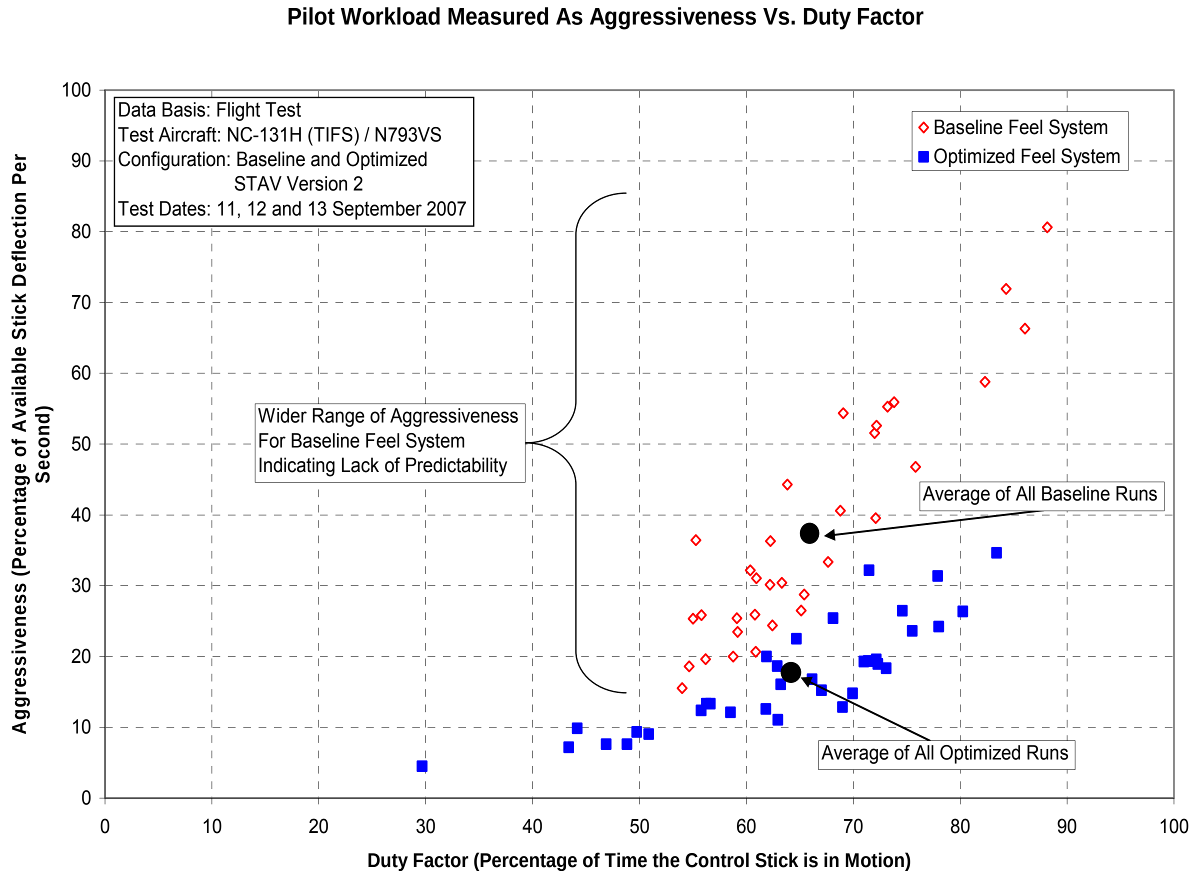

Figure 44 – TIFS Pilot Aggressiveness vs. Duty Factor

Unlike LAMARS, where there were no apparent significant differences between the baseline and optimized systems, the TIFS data did portray differences between the two systems with regard to their workload. The wide range of aggressiveness for the baseline system indicated a lack of predictability, as a highly predictable system would have required the same aggressiveness on each approach. On average, the optimized system required roughly half of the aggressiveness and a slightly decreased duty cycle compared to the baseline system. These quantitative descriptions correlated well with the pilots' comments of increased predictability and reduced workload when flying with the optimized system. Similar to the LAMARS testing, the data again showed a general

relationship between pilot aggressiveness and duty factor for both systems. As the duty factor decreased the aggressiveness tended to decrease, and as the duty factor increased there was a corresponding increase in aggressiveness.

The differences between the two systems were most pronounced in the last fifteen feet above simulated touchdown. The sensitivity of the baseline system prevented precise control and sometimes led to mild, recognized pitch PIOs as the distance to the runway decreased. The increased inceptor forces of the optimized system allowed for more predictable control and for better perception and correction of small changes in pitch near touchdown. The baseline system produced a sinking sensation at these low altitudes, while the optimized system did not. The PIO characteristics for the baseline system were all rated “1” except for two cases. In one instance, an overshoot in pitch correction at 10 feet AGL resulted in tight control leading to pitch oscillations that were not divergent, and a PIO rating of 4. In another instance, turbulence on final approach resulted in undesirable pitch motions (2-3 cycles) which tended to occur but did not affect task performance. No PIO tendencies were observed with the optimized system, as shown in figure E-6 in appendix E.

Table E-1 in appendix E summarizes the performance for all inadequate landings. Many of the baseline system landings failed to meet adequate performance for more than one criterion, while the optimized system had only one landing with more than one criterion failed. During the optimized system landings the aft part of the STAV never had a simulated runway strike, likely because the increased inceptor force inhibited the pilot from making rapid pulls while close to the runway. The optimized system inadequate landings were often a trade-off between longitudinal displacement and sink

rate, both of which relied on the longitudinal inceptor inputs during the flare. The reason for an inadequate landing therefore depended heavily upon a pilot's flare technique. Pilots who attempted to maintain a certain flight path angle and used open-loop inputs to correct one parameter at a time generally performed the best. Pilots who attempted to round out the flare and control the sink rate and landing distance simultaneously usually could not do so. Additionally, pilots who attempted this second method would tend to float down the runway, and it was only during this flare technique that the aft part of the STAV would have a simulated runway strike. The open-loop flare technique became the preferred landing method.

As shown by the data, pilots preferred the higher inceptor gradient of the LAMARS optimized control system during the approach and landing phases, but the timing of the gradient shift was undesirable. During simulator testing, the change in gradient at 100 feet AGL was not objectionable to the pilots, as very few inceptor inputs were required above this altitude. Although the change was too abrupt, pilots did not object to the timing of the change. However, during flight testing, turbulence required frequent pilot inputs above 100 feet AGL. Pilots became accustomed to the required inceptor inputs above 100 feet AGL, and then the gradient changed, which required compensation. The gradient change timing had a negative impact on the approach and landing HQ.

When testing in LAMARS, pilots required very few lateral corrections below 100 feet AGL. However, during flight test, turbulence and wind gusts required pilots to make low altitude lateral corrections. Since the force gradient was increased only in the longitudinal direction, the lateral inceptor movements remained overly sensitive, and

pilots commented that the control harmony was poor. In an aircraft with good control harmony, the forces required to make both lateral and longitudinal inceptor inputs will tend to match. If the force required to move the inceptor in one axis is significantly different from that required in another axis, then the control harmony is considered to be poor. The poor control harmony present on STAV decreased roll control predictability and led to over-controlling in the roll axis when pilots corrected for turbulence or wind gusts.

4.4.3 Flying Qualities Determination and Comparison

The final test objective was to determine the flying qualities for the TIFS simulation of the STAV flight control system. Several Programmed Test Inputs (PTI) and semi-open-loop capture tasks were performed on downwind in order to accomplish this objective. The PTI included pitch doublets, steps and frequency sweeps, roll steps, and yaw doublets and steps. Capture tasks were completed in pitch, roll, and heading. The baseline system was the only system tested during all flying qualities maneuvers, as the optimized system did not engage until 100 feet AGL. Figure 45 shows a time history of a pitch doublet and the STAV model pitch rate response. Figure 46 shows a time history of a yaw doublet and the STAV model angle of sideslip response.

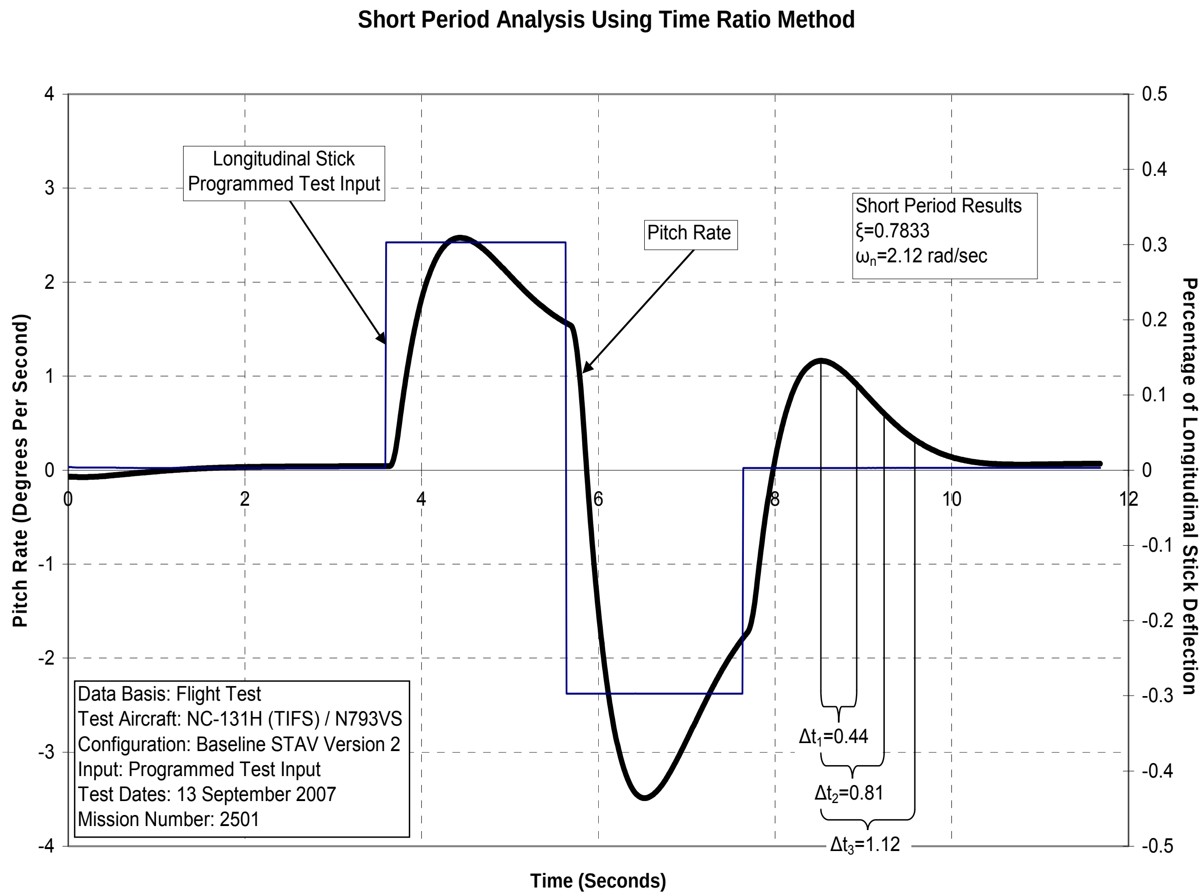

Figure 45 – Short Period Analysis Using Time Ratio Method

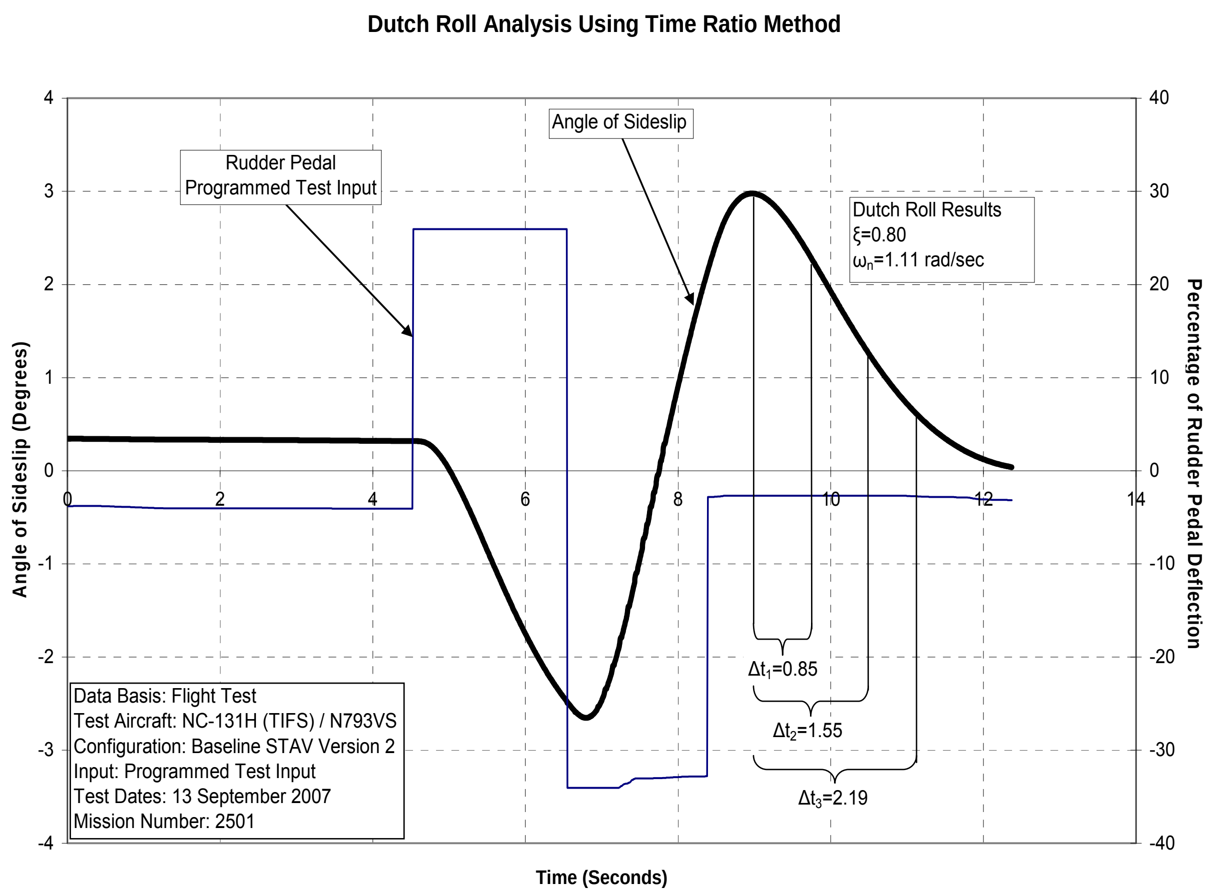

Figure 46 – Dutch Roll Analysis Using Time Ratio Method

Table 17 shows the short period damping ratio and natural frequency as determined using the time ratio method due to the large damping ratio. It also shows the Dutch roll damping ratio and natural frequency, which were again determined using the time ratio method (Yechout, 2003) due to the large damping ratio. Both the short period and Dutch roll damping ratios and natural frequencies were within the range of values considered satisfactory by MIL-STD 1797B. This information drove the test team investigation of other reasons for the poor STAV handling qualities.

Table 17 – Damping Ratio and Natural Frequency for TIFS/STAV

Mode	Damping Ratio	Natural Frequency
Short Period	0.78	2.12 radians/ sec
Dutch Roll	0.80	1.11 radians/ sec

Figure 47 shows a time history of a step PTI and the STAV model flight path angle response. Initially, pitch steps were two seconds in duration before the pilot recovered. The pitch step duration was then extended to five seconds to account for the low frequency of the short period. The initial flight path response was a small amplitude response in the opposite sense of the commanded input (a non-minimum phase response). After a delay of almost a second, the response began to more appropriately follow both the commanded sense and amplitude of the input. This time delay in flight path response contributed to the approach and landing unpredictability and led to the open-loop commands required for adequate landing performance.

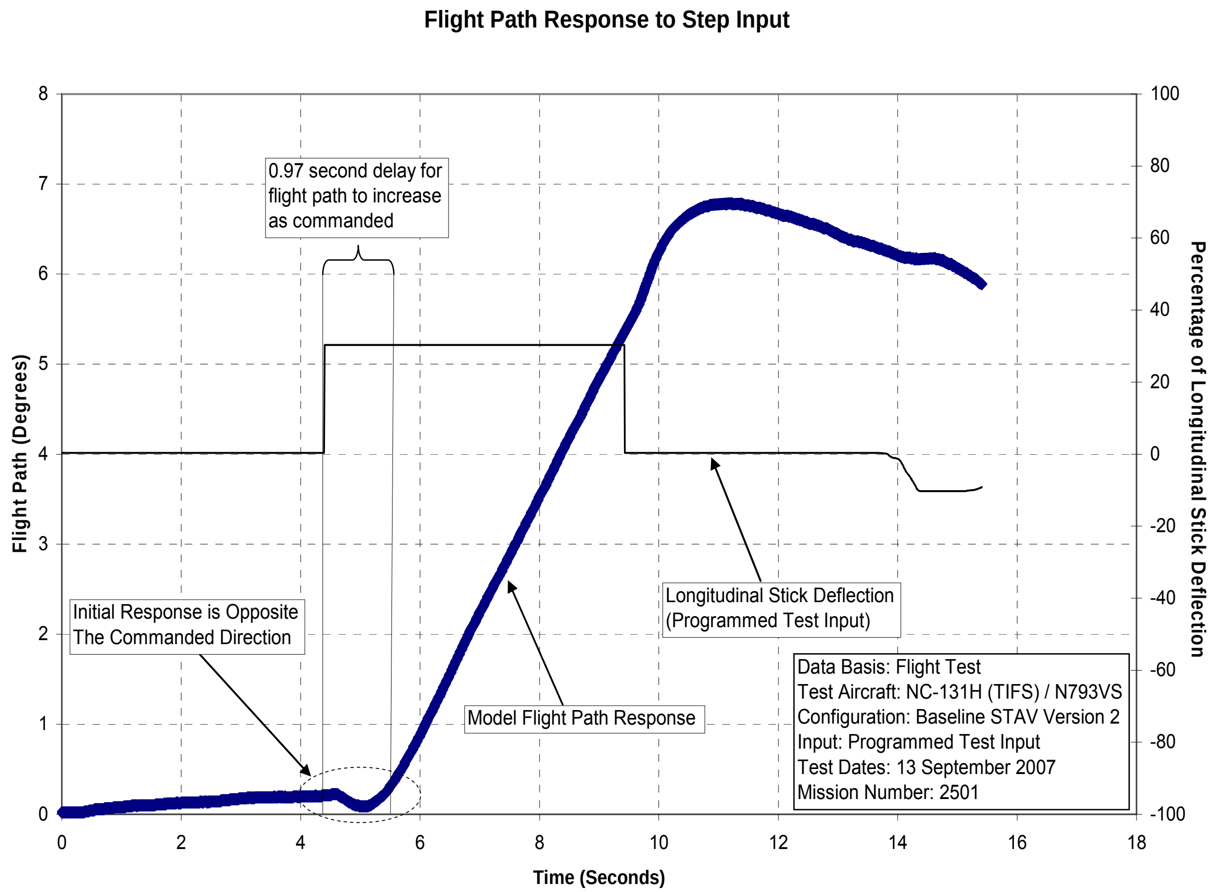

Figure 47 – Flight Path Response to Step Input

During the capture tasks, the pitch and roll performance appeared responsive for an aircraft the size of the STAV. The yaw response was slower than both pitch and roll, and was accompanied by a "heaving" feeling. Pitch captures typically had 2-3 overshoots, and the final attitude was difficult to predict, given the initial lag in flight path response. This was especially evident with large pitch commands. The pitch capture results were consistent with the flight path lag and baseline system inceptor sensitivity that adversely affected the approach and landing HQ.

Rolling into a bank required approximately five pounds of forward inceptor force to maintain level flight, and rolling out required a five pound pull. Roll "ratcheting" at

bank angles greater than twenty degrees caused small lateral and vertical heaving motions. Fifteen degree offset heading captures at bank angles of 15-20 degrees resulted in heading overshoots of about three degrees initially and two degrees after returning to wings level flight. The roll and heading behaviors were likely the result of a STAV flight control system alpha compensation feature that fed in angle of attack with roll to assist in aircraft maneuvering. Even with the sometimes undesirable motions, the roll and yaw capture tasks correlated well with the approach and landing handling qualities.

Overall, the TIFS followed the STAV model extremely well. Figures 48 and 49 show the STAV model response in pitch in both smooth and turbulent air, respectively. Accurate model-following was seen by both the similarity in shape and the magnitude of the peaks The model following displayed decreased accuracy in turbulent air, but this was due mostly to the engine response and spool-up time of the TIFS, and not the flight control system. Even though the accuracy degraded in turbulent air, the model following remained acceptable. The accurate model-following illustrated that the STAV handling qualities could be determined using the TIFS.

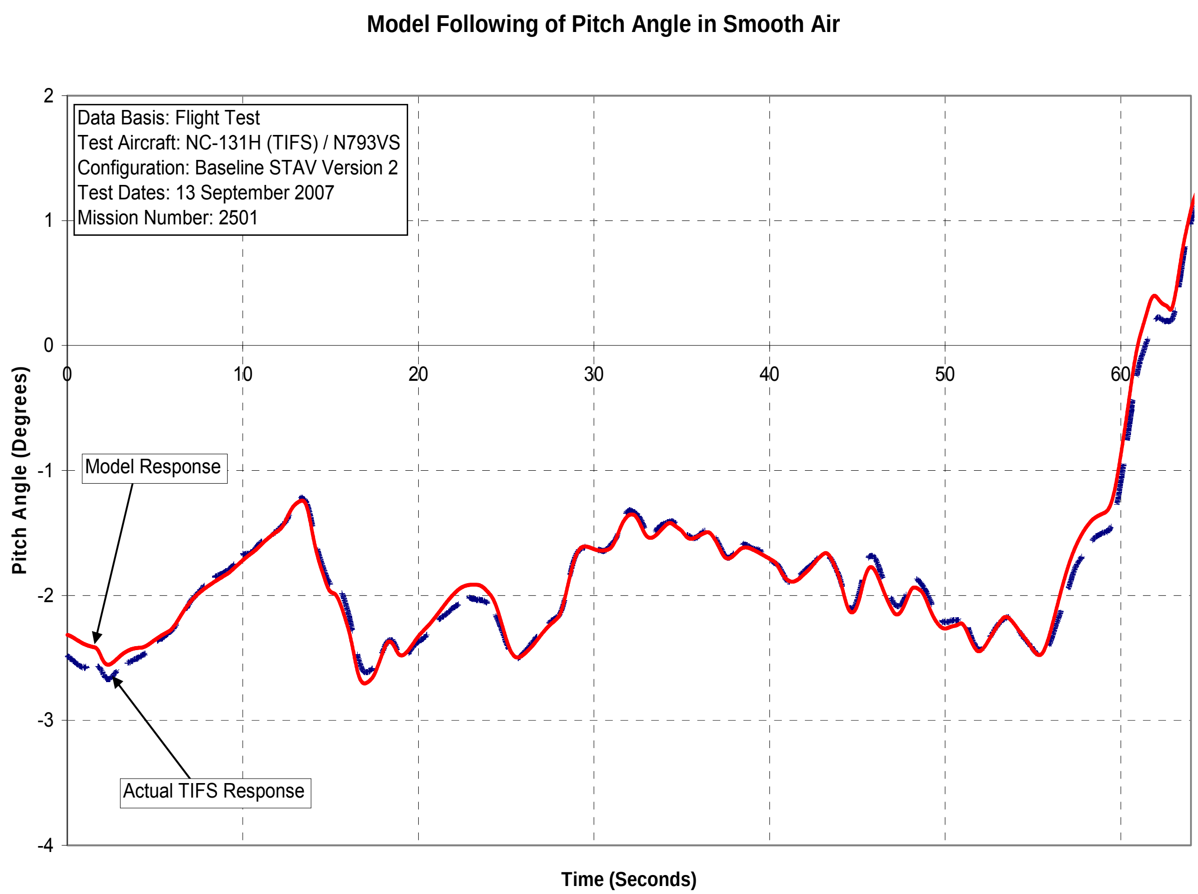

Figure 48 – Model Following of Pitch Angle in Smooth Air

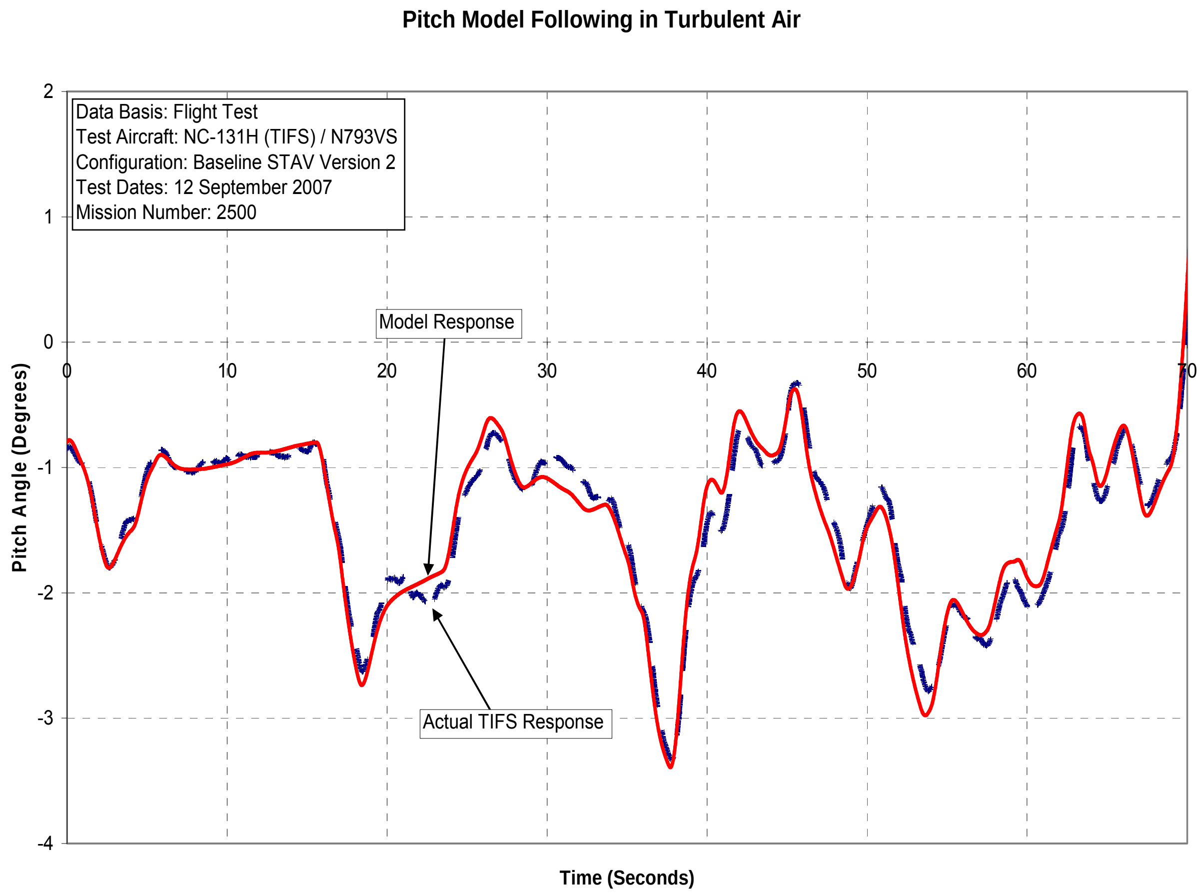

Figure 49 – Model Following of Pitch Angle in Turbulent Air

After analyzing the flight test results, some areas for improvement and possible underlying impacts on testing were proposed. The version 2 STAV model had better HQ than the first version, but remained Level 3 and required improvement. The number of approaches conducted during testing was limited. More testing would allow pilots to more clearly define the changes required to improve the system.

Pilot inputs at low altitude can rapidly become aggressive and large amplitude as the workload or stress is increased. A flight control system that could limit or compensate for unsafe pilot inputs at low altitude would increase safety in the approach and landing environment. This limit could be a dynamic stop, where a pilot would feel a

“soft” stop that indicated the normal safety limit. The pilot could go beyond this stop using increased force if dictated by safety of flight, but this soft stop would provide feedback to the pilot that the normal zone of travel for safe flight had been reached. This could help prevent unnecessarily large inceptor inputs during the flare. While version 2 of the STAV model did incorporate both ground effect and gear modeling, it did not account for control surface movements. There were multiple control surfaces used on STAV which were capable of actuating at tremendous rates. This could have had an impact on the STAV flight control system if the structural effects of these motions were fed back into the flight control algorithm. Further testing should study a higher fidelity STAV model that incorporated both of these changes.

Although the results from testing indicated that the up and away HQ were acceptable, testing should be conducted throughout the predicted aircraft mission envelope to see if any other flight regimes exhibit degraded HQ. The STAV had an eye height far above the ground, but this eye height was not simulated precisely in TIFS. The difference between the nominal STAV eye height and the TIFS simulated eye height was approximately ten feet, depending on approach angle of attack. This difference resulted from conducting low approaches to “touchdown” at twenty feet AGL, which increased the safety margin but limited the ground rush cues normally available to the pilots. The power reduction in TIFS was different than LAMARS. In LAMARS, landing required a reduction all the way to idle power. In TIFS the reduction required for landing was much smaller, and the landing power was well above idle. This difference in power reduction technique initially increased the workload, until the pilots adapted and the workload correspondingly decreased. As mentioned previously in this chapter, synthetic vision

will be a vital component to the STAV when flying it operationally, and the capabilities and employment of such a system need to be thoroughly investigated.

4.5 Summary

This chapter presented the results and analysis of all testing completed during this thesis. Each of the three main test sections: ICS testing, LAMARS testing, and TIFS testing, were shown in detail. The ICS results and analysis summarized the results first by aircraft, then by overall HQ rating and data precision, and finally by HQ rating and data precision according to pilot classification. The LAMARS and TIFS results and analysis covered the baseline and LAMARS optimized models, as well as the comparison between the two. They included pilot performance, CHR, and a measure of pilot workload vs. aggressiveness. Each section discussed: if the pilot ratings differed according to classification; ways to improve the test results; and underlying issues that hindered the tests or proved to be poor assumptions.

5.0 Conclusions and Recommendations

5.1 Overview

This chapter summarizes the thesis research, and includes both conclusions about the test data and recommendations for the future. The chapter is divided into the three main test sections: Infinity Cube Simulator (ICS) testing, Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS) testing, and Total In-Flight Simulator (TIFS) testing. In each section the conclusions are reviewed first. These conclusions not only summarize the data, but also explain why the results occurred. The recommendations of each section are then summarized, and consist of a list of things that can be done to refine or expand the testing, as well as possible areas to explore in future research. The chapter shows when the recommendations of one test section were used in another, as well as when they were not followed due to outside constraints or limitations.

5.2 Infinity Cube Simulator Testing

Several conclusions and recommendations were made concerning ICS testing. The version 1 STAV (Supersonic Tailless Air Vehicle) handling qualities (HQ) experienced during ICS testing were considered Level 2, and required improvement. The model itself required modification prior to conducting more approach and landing tests, because it did not include ground effect or gear modeling of the STAV. The ICS had a display brightness that was too low and a STAV model that could not be trimmed, two factors that negatively impacted pilot performance. Testing in ICS involved only approach and landing tasks, an evaluation of the entire STAV envelope would uncover any other areas with degraded HQ. Future testing should also include a synthetic vision evaluation, since the location of the STAV cockpit dictates the need for such a system.

Any further testing should be conducted in an airborne simulator with a variable stability system (VSS), as this would provide the highest-fidelity simulation.

The ICS testing showed that pilot background had an impact not only on Cooper-Harper rating (CHR), but also on the learning rate and the precision used to complete flying tasks. The use of a baseline aircraft was vital to ensure that pilots not trained in rating HQ were correctly using the Cooper-Harper rating (CHR) scale, and served as a basis by which the results of a group of non-test pilots could be compared to test pilot-generated historical data. However, test pilots should conduct formal HQ evaluations, because non-test pilots are less likely to discern the reasons behind poor HQ or identify proper methods for improvement. They are more apt to blame deficiencies on their own piloting skill than on the aircraft itself. Prior to rating an aircraft or task, the pilot should be able to practice the task as if they were an operational pilot. If a pilot is to perform at a high level with a limited workload during an approach and landing HQ evaluation, a heads up display (HUD) is critical, because it allows the pilot to simultaneously maintain situational awareness on both the parameters of the aircraft and the outside environment.

Evaluate an improved STAV model that accounted for ground effect and gear modeling. (R1)[1] The lack of ground effect led to a tendency to balloon in the flare. A STAV without a proper gear model will not be able to accurately assess the loads encountered during landing. An increased fidelity STAV model that accounted for both ground effect and gear modeling would mitigate these deficiencies. The version 2 STAV model used in subsequent LAMARS and TIFS testing incorporated these changes.

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[1] Numerals preceded by an R within parentheses at the end of a sentence correspond to the recommendation numbers of this thesis.

Use a full-motion simulator with better visuals and a trimmable model to provide a more realistic simulation. (R2) Full motion along with brighter visuals would improve the quality of the simulation by coupling the perceived visual response with the expected physical motion. A simulator able to operate a trimmable STAV model would more accurately evaluate pilot performance and CHR. LAMARS used a full-motion trimmable STAV model, but had a poorer visual capability than the ICS.

Conduct follow-on STAV testing beyond the approach and landing phase of flight. (R3) Testing throughout the entire operational mission envelope of the aircraft would provide a more thorough HQ evaluation, and would uncover any other areas of potentially degraded HQ. Future testing should investigate a larger flight envelope, as it was not possible given the scope of this thesis.

Conduct follow-on STAV testing using synthetic vision. (R4) Synthetic vision will be a vital component to the STAV when flying it operationally. This synthetic vision could range from conventional size heads down displays to large, panoramic displays that provide the pilot with a large visual field. Synthetic vision testing was limited by the scope of this thesis.

Conduct follow-on STAV testing on the VISTA or TIFS variable stability aircraft. (R5) The highest fidelity simulations are conducted in airborne simulators that have a variable stability system (VSS). A VSS would allow a pilot to fly in one aircraft while experiencing and evaluating the handling qualities of another. The TIFS aircraft was used to conduct flight tests of the STAV.

Use only test pilots when conducting a formal handling qualities evaluation. (R6) Pilots can and will have different backgrounds, but they should all have basic test

experience. Non-test pilots are not lacking in skill, they simply lack proper HQ training. Test pilots were used exclusively after ICS testing.

Conduct more practice approaches per pilot prior to assigning a formal CHR. (R7) This would allow any learning effects to take place prior to a formal CHR evaluation without any artificial workload decrease caused by excessive repetition of the task. Subsequent LAMARS and TIFS testing incorporated practice approaches into the test plan.

Use a HUD when conducting an approach and landing HQ evaluation. (R8) A HUD decreases workload because it allows the pilot to simultaneously perceive the outside environment and the aircraft parameters. A HUD does not have to be attached to the aircraft; it can also be something like a helmet-mounted display. A HUD was not used by in subsequent LAMARS and TIFS testing due to monetary and time constraints.

5.3 LAMARS Simulator Testing

LAMARS was excellent preparation for TIFS testing, as it provided a higher fidelity simulation than the ICS that allowed the team to test the baseline system, develop an optimized system, and refine the test methodology. However, brighter visuals in LAMARS with a wider field of view that allowed peripheral cueing would improve the fidelity and realism of the simulator. Turbulence was not implemented on LAMARS, and in future testing this should be looked at to determine the model response to wind gusts or turbulence prior to flight testing. This lack of turbulence drove an open-loop flying technique that prevented the pilots from perceiving a control harmony mismatch discovered during subsequent flight testing. The flare and landing were the most difficult part of each task, a result similar to both ICS and previous NGC LAMARS testing. This

was due in large part to the unpredictable sink rate, which limited the pilot's ability to increase workload and achieve desired performance.

The alpha-command control system selected as the best option for the baseline version 2 STAV model still had level 2 HQ at best during approach and landing. The benefits of the gamma-command system should be further studied, especially during low gain tasks. The optimized system also required improvement, but it was markedly better than the baseline system, and resulted in a more predictable flare. A blended inceptor gradient change would result in a less disruptive impact on the pilot during the approach. Both systems showed that pilots would usually trade-off between the sink rate and landing distance criteria, and that the pilot inputs became more aggressive as the time spent moving the inceptor increased. The use of altitude calls and a standardized power pull reduced pilot workload and increased consistency, and should be employed during flight testing. As in the ICS testing, the pilot should be able to practice a task as if they were an operational pilot prior to giving a CHR. The touchdown zone criteria should be resized to better reflect an operationally acceptable landing area. A crosscheck of the flying qualities of the STAV model as implemented on TIFS should be made to again ensure model fidelity during testing. Finally, the background of each pilot did not have a significant impact on the perceived HQ ratings.

Improve the LAMARS visuals by increasing the brightness and widening the field of view to allow peripheral cuing. (R9) The LAMARS displays were not bright or large enough to pick up on the subtle visual and peripheral cues that would be available when landing in the real world. While the LAMARS visuals were not improved, the view from the evaluation cockpit through the TIFS bubble canopy was excellent.

Blend the longitudinal gradient change over a time or altitude band to make it less perceptible. (R10) While the pilots liked the higher gradient and the timing of the change, they did not like how abrupt it was. This abrupt change served as a distraction to the pilots during the flare, effectively increasing the workload and decreasing the CHR. The gradient change in TIFS testing occurred over a 1.5 second time span.

Use altitude calls and a set power reduction to standardize the flare technique. (R11) Flare standardization improved repeatability and decreased the pilot workload, particularly with no HUD available. It minimized the differences between pilots during the flare. Flare standardization was used in TIFS, but had to be modified to account for a different power reduction technique.

Increase the longitudinal landing zone criteria. (R12) Current large bomber aircraft routinely land up to 2000 feet long of there intended touchdown point. This would allow the pilot a larger area to aim for, and would not artificially increase the pilot gain by attempting a spot landing on an area that was too small. The desired and adequate landing zones were both increased for TIFS testing, but these too proved to be somewhat restrictive. Operational requirements need to drive the landing zone criteria, which should be flexible enough to account for adverse weather or emergency conditions.

Crosscheck the flying qualities of a model as implemented on a simulator with the flying qualities of the model itself. (R13) Proper implementation of the model onto a simulator needs to be assured. If the flying qualities match, then the results from the simulations can be assumed to be the same as the results one would get when using the model itself. A series of steps, impulses, and simple capture tasks were performed on TIFS to make sure the flying qualities matched the baseline STAV model.

5.4 TIFS Flight Testing

The TIFS flight testing resulted in a number of conclusions and recommendations. As with the LAMARS testing conducted by the HAVE STAV test team, pilot background did not have a significant impact on the perceived HQ. The version 2 STAV model had better HQ than the first version, but remained unacceptable during approach and landing tasks. Pitch sensitivity was the most objectionable flight control characteristic when landing the baseline STAV model. The handling qualities of the optimized system were better than the baseline system, but required improvement. The unpredictable sink rate again limited the pilot's ability to increase workload and achieve desired performance. Sink rate remained the critical performance parameter of both systems during landing, and the trade-off between the sink rate and landing distance criteria occurred once more. Both systems showed that pilot inputs became more aggressive as the time spent moving the inceptor (duty cycle) increased. On average, the optimized system required roughly half of the aggressiveness and a slightly decreased duty cycle compared to the baseline system. The increased inceptor forces of the optimized system allowed for more predictable control and for better perception and correction of small changes in pitch near touchdown.

Turbulence, which was not encountered during encountered during ICS or LAMARS testing, increased the pilot workload during flight test and had an unexpected impact on CHR. Any decrease in pilot gain associated with the reduced 7-knot crosswind generation capability was more than made up for with the response to turbulence; therefore this reduction in crosswind capability had no real impact on testing. Alpha compensation generated by the flight control system during turns caused moments that

required the pilot to impart an unnatural push when rolling into a turn and an unnatural pull when rolling out of a turn. The approximately ten foot difference between the nominal STAV eye height and the TIFS simulated eye height increased the safety margin but limited the ground rush cues normally available to the pilots. An appropriate HUD would have improved the flight path and sink rate awareness needed during the visual portion of the landing. Combining the current aircraft parameters with some sort of predictive guidance information from a flight director or predictive flight path marker would increase the STAV flight predictability, particularly during the flare and landing. As shown in LAMARS testing, a crosscheck of the flying qualities of a model as implemented on a simulator should always be made to ensure model fidelity during testing. Again as in both ICS and LAMARS testing, the pilot should be able to practice a task as if they were an operational pilot prior to giving a CHR, while an evaluation of the entire STAV envelope would uncover any other areas with degraded HQ. Since the location of the STAV cockpit dictates the need for synthetic vision, future testing should include such an evaluation. This evaluation should also involve both a HUD and predictive guidance, as these three systems would be heavily integrated in the STAV.

The time delay in flight path response inherent in the flight control system negatively affected aircraft predictability in the pitch axis during approach and landing. The timing of the increase in inceptor force gradient was inappropriate, and forced pilots to dramatically increase workload at low altitudes. The lateral inceptor force gradient did not change when the longitudinal gradient increased, and this adversely affected control harmony. The results of both systems showed that pilot inputs at low altitude can rapidly become aggressive and large amplitude as the workload or stress is increased, causing a

potentially dangerous situation. While version 2 of the STAV model did incorporate both ground effect and gear modeling, it did not account for the multiple control surface movements present when maneuvering, which could have an impact on the STAV flight control system if the structural effects of these motions were fed back into the flight control algorithm.

Increase the inceptor force gradient for approach and landing. (R14) Baseline inceptor gains were too low during approach and landing, resulting in a loose feel, objectionable inceptor sensitivity, and increased duty cycle and aggressiveness. Any increase in inceptor force gradient should include both longitudinal and lateral changes in order to preserve control harmony.

Test a model's response to turbulence prior to flight testing. (R15) Turbulence can have an impact both on the pilot workload and on the model following capabilities of a simulation. Testing in turbulence would better simulate real world conditions and an aircraft's response to those conditions. Investigating turbulence prior to flight testing would save both time and money

Reduce the amount of alpha compensation generated during turns. (R16) When attempting to compensate for the increased angle of attack in a turn by generating a pitching moment to aid the pilot, the flight control system overcompensated with too high a moment that forced unnatural pilot inputs.

Implement a HUD on the STAV. (R17) A HUD would have provided simultaneous situational awareness of both the aircraft parameters and the outside environment. In addition, previous NGC LAMARS testing indicated that powered approach and landing handling qualities were improved when using a HUD.

Implement predictive guidance on the STAV. (R18) This predictive guidance would provide the pilot information on what the aircraft parameters would be in the near term future if no inputs were made to the throttles or inceptor, and could guide pilot inputs in order to achieve desired landing performance. Predictive guidance could be employed on a HUD using synthetic vision to aid the pilot not only during approach and landing, but also during other more mission-critical tasks.

Reduce the time delay in flight path response. (R19) Time delay in flight path response, on the order of one second, reduced predictability of pitch inputs and resulted in open-loop, methodical pilot compensation during approach and landing. A reduction in the flight path response time delay would result in improved HQ.

Provide more time for the pilot to acclimate to inceptor force gradient changes prior to touchdown. (R20) Pilots commented that it would have been desirable to have the same inceptor force gradient for the entire final approach. The timing of such an inceptor force gradient change could be similar to another highly-augmented military aircraft, the F-16.

Change the lateral inceptor force gradient to preserve control harmony. (R21) With no increase in force gradient the lateral inceptor movements remained overly sensitive, resulting in a poor control harmony that decreased roll control predictability and led to over-controlling in the roll axis when pilots corrected for turbulence or wind gusts.

Implement automatic approach and landing safety compensation on the STAV. (R22) A flight control system that could limit or compensate for unsafe pilot inputs at low altitude would increase safety in the approach and landing environment.

Implement a higher-fidelity STAV model that accounted for the impact of control surface movements on the flight control system. (R23) There were multiple control surfaces capable of actuating at tremendous rates used on STAV, which could potentially feed back into the flight control algorithm. Further testing should study a higher fidelity STAV model that accounted for these movements.

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Vita

Captain Steven W. Speares was born and raised in Rochester, New York, and entered the United States Air Force Academy (USAFA) in 1995, where he graduated with a Bachelor of Science degree in Astronautical Engineering and a minor in Mathematics. He was commissioned as a Second Lieutenant and moved to Columbus AFB, Mississippi for pilot training in Specialized Undergraduate Pilot Training (SUPT). Captain Speares completed the course and was assigned to fly the F-15E at Seymour Johnson AFB, North Carolina, where he served as a combat fighter pilot of the 336 FS Rocketeers. From January to May of 2003 he flew 46 combat missions in Operations Southern Watch and Iraqi Freedom, and was awarded two Distinguished Flying Crosses for his combat actions. While at Seymour Johnson, Captain Speares was selected to the Air Force Institute of Technology/Test Pilot School (AFIT/TPS) program. He participated in initial STAV simulator testing conducted by the NGC in LAMARS in the spring of 2006. He was a top third graduate of USAF Test Pilot School Class 07A and is currently assigned to the 445th Test Operations Squadron at Edwards AFB. He has over 1200 hours in over thirty different aircraft, including 850 in the F-15E.

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Appendix A – Additional Infinity Cube Simulator Results

Table A-1 – ICS CHR Summary

Pilot Type	T38 LO	T38 LA	175 LO	175 LA	195 LO	195 LA
Overall Mean	3.07	2.94	5.22	5.09	4.98	4.91
Overall σ	1.30	1.19	1.73	1.85	1.60	1.59
USAF Mean	3.34	3.20	5.68	5.31	4.95	4.81
USAF σ	1.31	1.27	1.78	1.92	1.55	1.63
Navy Mean	2.50	2.42	4.23	4.75	4.92	5.00
Navy σ	1.20	1.00	1.33	1.83	1.94	1.76
Fighter Mean	3.30	2.89	5.33	5.25	4.79	4.65
Fighter σ	0.97	1.19	1.68	2.05	1.55	1.63
Heavy Mean	2.81	3.00	5.11	4.92	5.19	5.19
Heavy σ	1.60	1.09	2.00	1.99	1.76	1.78
Non-test Mean	3.03	3.81	4.89	4.72	4.80	4.72
Non-test σ	1.33	1.10	1.53	1.69	1.61	1.60
Test Mean	3.25	3.63	7.00	7.08	5.96	5.92
Test σ	1.18	1.63	1.67	1.33	0.98	1.20

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Appendix B – LAMARS Test Matrix

Table B-1 – LAMARS Test Matrix

Key of Abbreviations in Modeling and Simulation Matrix			
Pilot		**Task**	
1	Speares	N	Normal
2	Domsalla	L	Lateral Offset
3	Quashnock	V	Vertical Offset
4	Gray	**Feel System**	
Control Type		B	Baseline
A	Alpha	IS	Inc Inceptor Force
G	Gamma	SP	Spoiler Reset
P	Pitch Rate	IS/SP	Combined
Crosswind		**Airspeed**	
O	Zero	L	175
M	Max	H	195

Hour #	Pilot	Run #	Control Type	Feel System	Airspeed	Task	Crosswind
1	1	1	A	B	L	N	O
1	1	2	A	B	L	N	O
1	1	3	A	B	L	N	O
1	1	4	A	B	L	N	M
1	1	5	A	B	L	L	O
1	1	6	A	B	L	L	M
1	1	7	A	B	H	N	O
1	1	8	A	B	H	N	M
1	1	9	A	B	H	L	O
1	1	10	A	B	H	L	M
2	1	1	G	B	L	N	O
2	1	2	G	B	L	L	M
2	1	3	G	B	H	N	O
2	1	4	G	B	H	L	M
2	1	5	P	B	L	N	O
2	1	6	P	B	L	L	M
2	1	7	P	B	H	N	O
2	1	8	P	B	H	L	M
2	1	9	A	B	L	V	O
2	1	10	A	B	L	V	M
3	2	1	A	B	L	N	O
3	2	2	A	B	L	N	O
3	2	3	A	B	L	N	O
3	2	4	A	B	L	N	M
3	2	5	A	B	L	L	O
3	2	6	A	B	L	L	M
3	2	7	A	B	H	N	O
3	2	8	A	B	H	N	M
3	2	9	A	B	H	L	O
3	2	10	A	B	H	L	M

Table B-1 – LAMARS Test Matrix (Continued)

Hour #	Pilot	Run #	Control Type	Feel System	Airspeed	Task	Crosswind
4	2	1	G	B	L	N	O
4	2	2	G	B	L	L	M
4	2	3	G	B	H	N	O
4	2	4	G	B	H	L	M
4	2	5	P	B	L	N	O
4	2	6	P	B	L	L	M
4	2	7	P	B	H	N	O
4	2	8	P	B	H	L	M
4	2	9	A	B	H	V	O
4	2	10	A	B	H	V	M
5	3	1	A	B	L	N	O
5	3	2	A	B	L	N	O
5	3	3	A	B	L	N	O
5	3	4	A	B	L	N	M
5	3	5	A	B	L	L	O
5	3	6	A	B	L	L	M
5	3	7	A	B	H	N	O
5	3	8	A	B	H	N	M
5	3	9	A	B	H	L	O
5	3	10	A	B	H	L	M
6	3	1	G	B	L	N	O
6	3	2	G	B	L	L	M
6	3	3	G	B	H	N	O
6	3	4	G	B	H	L	M
6	3	5	P	B	L	N	O
6	3	6	P	B	L	L	M
6	3	7	P	B	H	N	O
6	3	8	P	B	H	L	M
6	3	9	A	B	L/H	V	O
6	3	10	A	B	L/H	V	M
7	1	1	A	IS	L/H	N	O
7	1	2	A	IS	L/H	N	M
7	1	3	A	IS	L/H	L	O
7	1	4	A	IS	L/H	L	M
7	1	5	A	IS	L/H	N	O
7	1	6	A	IS	L/H	N	M
7	1	7	A	IS	L/H	L	O
7	1	8	A	IS	L/H	L	M
7	1	9	A	IS	L/H	N	O
7	1	10	A	IS	L/H	L	M
8	2	1	A	IS	L/H	N	O
8	2	2	A	IS	L/H	N	M
8	2	3	A	IS	L/H	L	O
8	2	4	A	IS	L/H	L	M
8	2	5	A	IS	L/H	N	O
8	2	6	A	IS	L/H	N	M
8	2	7	A	IS	L/H	L	O
8	2	8	A	IS	L/H	L	M
8	2	9	A	SP	L/H	N	O
8	2	10	A	SP	L/H	L	M

Table B-1 – LAMARS Test Matrix (Continued)

Hour #	Pilot	Run #	Control Type	Feel System	Airspeed	Task	Crosswind
9	3	1	A	IS	L/H	N	O
9	3	2	A	IS	L/H	N	M
9	3	3	A	IS	L/H	L	O
9	3	4	A	IS	L/H	L	M
9	3	5	A	SP	L/H	N	O
9	3	6	A	SP	L/H	N	M
9	3	7	A	SP	L/H	L	O
9	3	8	A	SP	L/H	L	M
9	3	9	A	SP	L/H	N	O
9	3	10	A	SP	L/H	L	M
10	1	1	A	B	L	N	O
10	1	2	A	SP	L/H	N	O
10	1	3	A	SP	L/H	N	M
10	1	4	A	SP	L/H	L	O
10	1	5	A	SP	L/H	L	M
10	1	6	A	IS/SP	L/H	N	O
10	1	7	A	IS/SP	L/H	N	M
10	1	8	A	IS/SP	L/H	L	O
10	1	9	A	IS/SP	L/H	L	M
10	1	10	G/P	IS/SP	L/H	N	O
11	2	1	A	B	L	N	O
11	2	2	A	SP	L/H	N	O
11	2	3	A	SP	L/H	N	M
11	2	4	A	SP	L/H	L	O
11	2	5	A	SP	L/H	L	M
11	2	6	A	IS/SP	L/H	N	O
11	2	7	A	IS/SP	L/H	N	M
11	2	8	A	IS/SP	L/H	L	O
11	2	9	A	IS/SP	L/H	L	M
11	2	10	G/P	IS/SP	L/H	N	O
12	3	1	A	B	L	N	O
12	3	2	A	IS/SP	L/H	N	O
12	3	3	A	IS/SP	L/H	N	M
12	3	4	A	IS/SP	L/H	L	O
12	3	5	A	IS/SP	L/H	L	M
12	3	6	G	IS/SP	L/H	N	O
12	3	7	G	IS/SP	L/H	L	M
12	3	8	P	IS/SP	L/H	N	O
12	3	9	P	IS/SP	L/H	L	M
12	3	10	G/P	IS/SP	L/H	N	M
13	4	1	A	B	L	N	O
13	4	2	A	B	L/H	N	O
13	4	3	A	B	L/H	N	M
13	4	4	A	B	L/H	L	O
13	4	5	A	B	L/H	L	M
13	4	6	A	IS/SP	L/H	N	O
13	4	7	A	IS/SP	L/H	N	M
13	4	8	A	IS/SP	L/H	L	O
13	4	9	A	IS/SP	L/H	L	M
13	4	10	G/P	IS/SP	L/H	N	O

Table B-1 – LAMARS Test Matrix (Continued)

Hour #	Pilot	Run #	Control Type	Feel System	Airspeed	Task	Crosswind
14	1	1	A	IS/SP	L	V	O
14	1	2	A	IS/SP	L	V	M
14	1	3	A	IS/SP	H	V	O
14	1	4	A	IS/SP	H	V	M
14	1	5	G	IS/SP	L	V	O
14	1	6	G	IS/SP	H	V	O
14	1	7	G	IS/SP	L/H	V	M
14	1	8	P	IS/SP	L	V	O
14	1	9	P	IS/SP	H	V	O
14	1	10	P	IS/SP	L/H	V	M
15	2	1	A	IS/SP	L	V	O
15	2	2	A	IS/SP	L	V	M
15	2	3	A	IS/SP	H	V	O
15	2	4	A	IS/SP	H	V	M
15	2	5	G	IS/SP	L	V	O
15	2	6	G	IS/SP	H	V	O
15	2	7	G	IS/SP	L/H	V	M
15	2	8	P	IS/SP	L	V	O
15	2	9	P	IS/SP	H	V	O
15	2	10	P	IS/SP	L/H	V	M
16	3	1	A	IS/SP	L	V	O
16	3	2	A	IS/SP	L	V	M
16	3	3	A	IS/SP	H	V	O
16	3	4	A	IS/SP	H	V	M
16	3	5	G	IS/SP	L	V	O
16	3	6	G	IS/SP	H	V	O
16	3	7	G	IS/SP	L/H	V	M
16	3	8	P	IS/SP	L	V	O
16	3	9	P	IS/SP	H	V	O
16	3	10	P	IS/SP	L/H	V	M
17	Neff	1	A	B	L/H	N	O
17	Neff	2	A	B	L/H	L	O
17	Neff	3	A	B	L/H	L	M
17	Neff	4	A	IS/SP	L/H	N	O
17	Neff	5	A	IS/SP	L/H	L	O
17	Neff	6	A	IS/SP	L/H	L	M
17	Cook	1	A	B	L/H	N	O
17	Cook	2	A	B	L/H	L	O
17	Cook	3	A	B	L/H	L	M
17	Cook	4	A	IS/SP	L/H	N	O
18	Cook	5	A	IS/SP	L/H	L	O
18	Cook	6	A	IS/SP	L/H	L	M
18	Porter	1	A	B	L/H	N	O
18	Porter	2	A	B	L/H	L	O
18	Porter	3	A	B	L/H	L	M
18	Porter	4	A	IS/SP	L/H	N	O
18	Porter	5	A	IS/SP	L/H	L	O
18	Porter	6	A	IS/SP	L/H	L	M

Appendix C: Test Cards

Infinity Cube Simulator Test Cards

The following test cards were used during the Infinity Cube Simulator (ICS) testing. Prior to testing, all cards were briefed in detail to the pilots.

TASK ID STAV-1 SIM | **TASK** Precision Approach and Landing | UNCLASSIFIED | HAVE STAV

FLIGHT PHASE	TASK DESCRIPTION	
Approach and Landing	Approach and Landing	

FIXED PARAMETERS

Wind: Calm Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 8 NM out Initial Speed: 220 knots Initial Heading: On LOC ALT: 1500 ft Landing Speed: 160 knots	GW: 232683 lb for STAV CG pos FS: 1044.14 in BL: -0.04 in WL: 107.27

VARIED PARAMETERS

Approach Airspeed: 195, 175 knots					

TEST PROCEDURE

PILOT

1. Establish aircraft in steady level flight at the initial conditions.
2. Slow to approach speed from 220 knots with engine throttles.
3. Capture approach speed.
4. Track LOC to G/S intercept and capture G/S (3 deg).
5. Continue approach to landing. Touchdown target is designated on runway (CAPT bars).

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record parameters at 1000 ft AGL and touchdown.

PILOT	DATE	RUN NUMBER

EVALUATION SEGMENT 1	LONG CHR	LAT/DIR CHR
Glideslope intercept and Localizer track		

Start Evaluation: 1500 ft, Approach speed, Level
End Evaluation: 400 ft AGL, Approach speed, Descending

EVALUATION BASIS

Evaluate the ability to maneuver onto and track the final approach path. Attain trimmed flight before the middle marker (approx 0.5 nm from the end of the runway).

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Deviation from Approach A/S (KEAS)	0	+/ - 5	+/ - 10
Deviation from Glideslope	0	+/ - 0.5 dot	+/ - 1.0 dot
Deviation from Localizer	0	+/ - 0.5 dot	+/ - 1.0 dot

EVALUATION SEGMENT 2	LONG CHR	LAT/DIR CHR
Precision Landing		

Start Evaluation: 400 ft AGL, Approach speed, Descending
End Evaluation: Touchdown

EVALUATION BASIS

Evaluate handling qualities of the airplane during landing. There should be no tendency to bobble in pitch or roll or for PIOs.

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Aim Point	50 x 500	100 x 1000
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Deviation from Land A/S @ Touchdown (KEAS)	0	+/ - 5	+/ - 10
Maximum Touchdown Sink Rate (ft/ sec)	<6	6	10
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

UNCLASSIFIED

Figure C-1 – ICS Test Card 1

TASK ID **TASK**

STAV-2 SIM **Lateral Offset Landing**

UNCLASSIFIED

HAVE STAV

FLIGHT PHASE	**TASK DESCRIPTION**
Landing	Precision Landing from Lateral Offset

FIXED PARAMETERS

Wind: Calm Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 8 NM out Initial Speed: 220 knots Initial Heading: On LOC ALT: 1500 ft Landing Speed: 160 knots	Lat Offset: +/- 200 ft offset from LOC Cloud Breakout: 300 ft AGL GW: 232683 lb for STAV CG pos: Same as 1

VARIED PARAMETERS

Approach Airspeed: 195, 175 knots					

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. At “cloud breakout”, visually correct course to recapture runway centerline.
3. Continue to fly final approach until touchdown.
4. Touchdown target is designated on runway.

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record parameters at touchdown.

PILOT	**DATE**	**RUN NUMBER**

EVALUATION SEGMENT	**LONG CHR**	**LAT/DIR CHR**
Precision Landing from Lateral Offset		

Start Evaluation: 600 ft AGL, Approach speed, Descending
End Evaluation: Touchdown

EVALUATION BASIS

Evaluate the handling qualities in landing in a high-gain task. There should be no tendency to bobble in pitch or roll or for PIOs.

PERFORMANCE STANDARDS	**TARGET**	**DESIRED**	**ADEQUATE**
Landing Zone (for ref. point btwn main gear) (ft)	Aim Point	50x500	100x1000
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Deviation from Land A/S @ Touchdown (KEAS)	0	+/ - 5	+/ - 10
Maximum Touchdown Sink Rate (ft/ sec)	<6	6	10
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

UNCLASSIFIED

Figure C-2 – ICS Test Card 2

TASK ID	TASK	UNCLASSIFIED	HAVE STAV
STAV-3 SIM	Vertical Offset Landing		

FLIGHT PHASE	TASK DESCRIPTION	PILOT	DATE	RUN NUMBER
Landing	Precision Landing from Vertical Offset			

FIXED PARAMETERS

Wind: Calm Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 8 NM out Initial Speed: 220 knots Initial Heading: On LOC ALT: 1500 ft Landing Speed: 160 knots	Long Offset: + 50 ft vertical offset from G/S Cloud Breakout: 300 ft AGL GW: 232683 lb for STAV CG pos: Same as 1

VARIED PARAMETERS

Approach Airspeed: 195, 175 knots					

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. At “cloud breakout”, visually correct glideslope to make touchdown at target. Maintain desired vertical velocity and approach speed.
3. Continue to fly final approach until touchdown.
4. Touchdown target is designated on runway.

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record parameters at touchdown.

EVALUATION SEGMENT	LONG CHR	LAT/DIR CHR
Precision Landing from Lateral Offset		

Start Evaluation: 600 ft AGL, Approach speed, Descending
End Evaluation: Touchdown

EVALUATION BASIS

Evaluate the handling qualities in landing in a high-gain task. There should be no tendency to bobble in pitch or roll or for PIOs.

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Aim Point	50x500	100x1000
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Deviation from Land A/S @ Touchdown (KEAS)	0	+/ - 5	+/ - 10
Maximum Touchdown Sink Rate (ft/ sec)	<6	6	10
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

UNCLASSIFIED

Figure C-3 – ICS Test Card 3

LAMARS Test Cards

The following test cards were used during LAMARS testing at Wright-Patterson AFB, OH.

TASK ID **TASK** UNCLASSIFIED HAVE STAV

STAV-1 CALM **Precision Landing**

FLIGHT PHASE Landing / **TASK DESCRIPTION** Precision Landing from Normal Approach	**PILOT** / **DATE** / **RUN NUMBER**
FIXED PARAMETERS Wind: Calm Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete Initial Position: 4 NM out Initial Speed: 200 knots Initial Heading: On LOC ALT: 1000 ft AGL Landing Speed: V_{app}-10 GW: 232683 lb for STAV CG pos FS: 1044.14 in BL: -0.04 in WL: 107.27	**EVALUATION SEGMENT** / **CHR** Precision Landing from Normal approach Start Evaluation: 600 ft AGL, Approach speed, Descending End Evaluation: Simulated Touchdown **EVALUATION BASIS** Evaluate handling qualities when landing in a high-gain task. There should be no tendency to bobble in pitch or roll for PIOs.

VARIED PARAMETERS

Approach Airspeed:	175	195			
Control System:			Alpha	Gamma	Pitch Rate

PERFORMANCE STANDARDS

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Aim Point	50 x 500	100 x 1000
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Deviation from Land A/S @ Touchdown (KEAS)	0	+/ - 5	+/ - 10
Maximum Touchdown Sink Rate (ft/ sec)	<4	4	6
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. Continue to fly final approach until flare.
3. Touchdown target is designated on runway.

FEEL SYSTEM

Baseline

Aft Stick Gain = ____________

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record task and performance parameters at simulated touchdown.

PILOT TECHNIQUE

Baseline

Spoilers in at _______ AGL

UNCLASSIFIED

Figure C-4 – LAMARS Test Card 1

TASK ID	TASK		
STAV-1 XW	Precision Landing	UNCLASSIFIED	HAVE STAV

FLIGHT PHASE	TASK DESCRIPTION	PILOT	DATE	RUN NUMBER
Landing	Precision Landing from Normal Approach			

FIXED PARAMETERS

Wind: 15 knots crosswind Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 4 NM out Initial Speed: 200 knots Initial Heading: On LOC ALT: 1000 ft AGL Landing Speed: V_{app}-10	GW: 232683 lb for STAV CG pos FS: 1044.14 in BL: -0.04 in WL: 107.27

VARIED PARAMETERS

Approach Airspeed:	175	195			
Control System:			Alpha	Gamma	Pitch Rate

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. Continue to fly final approach until flare.
3. Touchdown target is designated on runway.

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record task and performance parameters at simulated touchdown.

EVALUATION SEGMENT | **CHR**

Precision Landing from Normal approach

Start Evaluation: 600 ft AGL, Approach speed, Descending
End Evaluation: Simulated Touchdown

EVALUATION BASIS

Evaluate handling qualities when landing in a high-gain task. There should be no tendency to bobble in pitch or roll for PIOs.

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Aim Point	50 x 500	100 x 1000
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Deviation from Land A/S @ Touchdown (KEAS)	0	+/ - 5	+/ - 10
Maximum Touchdown Sink Rate (ft/ sec)	<4	4	6
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

FEEL SYSTEM

Baseline

Aft Stick Gain = ____________

PILOT TECHNIQUE

Baseline

Spoilers in at _______ AGL

UNCLASSIFIED

Figure C-5 – LAMARS Test Card 2

TASK ID STAV-2 CALM | TASK Lateral Offset Landing | UNCLASSIFIED | HAVE STAV

FLIGHT PHASE	TASK DESCRIPTION	PILOT	DATE	RUN NUMBER
Landing	Precision Landing from Lateral Offset			

FIXED PARAMETERS

Wind: Calm Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 4 NM out Initial Speed: 200 knots Initial Heading: On LOC ALT: 1000 ft AGL Landing Speed: V_{app}-10	Lat Offset: +/- 200 ft offset from LOC Cloud Breakout: 300 ft AGL GW: 232683 lb for STAV CG pos: Same as 1

VARIED PARAMETERS

Approach Airspeed:	175	195			
Control System:			Alpha	Gamma	Pitch Rate

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. At "cloud breakout", visually correct course to recapture runway centerline.
3. Continue to fly final approach until flare.
4. Touchdown target is designated on runway.

EVALUATION SEGMENT
Precision Landing from Lateral Offset

CHR

Start Evaluation: 600 ft AGL, Approach speed, Descending
End Evaluation: Simulated Touchdown

EVALUATION BASIS
Evaluate handling qualities when landing in a high-gain task. There should be no tendency to bobble in pitch or roll for PIOs.

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Aim Point	50 x 500	100 x 1000
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Deviation from Land A/S @ Touchdown (KEAS)	0	+/ - 5	+/ - 10
Maximum Touchdown Sink Rate (ft/ sec)	<4	4	6
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

FEEL SYSTEM

Baseline

Aft Stick Gain = ____________

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record task and performance parameters at simulated touchdown.

PILOT TECHNIQUE

Baseline

Spoilers in at _______ AGL

UNCLASSIFIED

Figure C-6 – LAMARS Test Card 3

TASK ID STAV-2 XW

TASK Lateral Offset Landing

UNCLASSIFIED

HAVE STAV

FLIGHT PHASE	TASK DESCRIPTION	PILOT	DATE	RUN NUMBER
Landing	Precision Landing from Lateral Offset			

FIXED PARAMETERS

Wind: 15 knots crosswind Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 4 NM out Initial Speed: 200 knots Initial Heading: On LOC ALT: 1000 ft AGL Landing Speed: V_{app}-10	Lat Offset: +/- 200 ft offset from LOC Cloud Breakout: 300 ft AGL GW: 232683 lb for STAV CG pos: Same as 1

EVALUATION SEGMENT — CHR

Precision Landing from Lateral Offset

Start Evaluation: 600 ft AGL, Approach speed, Descending
End Evaluation: Simulated Touchdown

EVALUATION BASIS

Evaluate handling qualities when landing in a high-gain task. There should be no tendency to bobble in pitch or roll for PIOs.

VARIED PARAMETERS

Approach Airspeed:	175	195			
Control System:			Alpha	Gamma	Pitch Rate

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Aim Point	50 x 500	100 x 1000
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Deviation from Land A/S @ Touchdown (KEAS)	0	+/ - 5	+/ - 10
Maximum Touchdown Sink Rate (ft/ sec)	<4	4	6
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. At “cloud breakout”, visually correct course to recapture runway centerline.
3. Continue to fly final approach until flare.
4. Touchdown target is designated on runway.

FEEL SYSTEM

Baseline

Aft Stick Gain = ____________

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record task and performance parameters at simulated touchdown.

PILOT TECHNIQUE

Baseline

Spoilers in at _______ AGL

UNCLASSIFIED

Figure C-7 – LAMARS Test Card 4

TASK ID **TASK**

STAV-3 CALM **Vertical Offset Landing**

UNCLASSIFIED

HAVE STAV

FLIGHT PHASE	TASK DESCRIPTION	PILOT	DATE	RUN NUMBER
Landing	Precision Landing from Vertical Offset			

FIXED PARAMETERS

Wind: Calm Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 4 NM out Initial Speed: 200 knots Initial Heading: On LOC ALT: 1000 ft AGL Landing Speed: V_{app}-10	Long Offset: + 50 ft vertical Offset from G/S (0.5 dot above) Cloud Breakout: 300 ft AGL GW: 232683 lb for STAV CG pos: Same as 1

VARIED PARAMETERS

Approach Airspeed:	175	195			
Control System:			Alpha	Gamma	Pitch Rate

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. At "cloud breakout", visually correct glideslope to make touchdown at target. Maintain desired vertical velocity and approach speed.
3. Continue to fly final approach until flare.
4. Touchdown target is designated on runway.

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record task and performance parameters at simulated touchdown.

EVALUATION SEGMENT — **CHR**

Precision Landing from Vertical Offset

Start Evaluation: 600 ft AGL, Approach speed, Descending
End Evaluation: Simulated Touchdown

EVALUATION BASIS

Evaluate handling qualities when landing in a high-gain task. There should be no tendency to bobble in pitch or roll for PIOs.

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Aim Point	50 x 500	100 x 1000
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Deviation from Land A/S @ Touchdown (KEAS)	0	+/ - 5	+/ - 10
Maximum Touchdown Sink Rate (ft/ sec)	<4	4	6
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

FEEL SYSTEM

Baseline

Aft Stick Gain = ____________

PILOT TECHNIQUE

Baseline

Spoilers in at _______ AGL

UNCLASSIFIED

Figure C-8 – LAMARS Test Card 5

TASK ID	TASK		
STAV-3 XW	Vertical Offset Landing	UNCLASSIFIED	HAVE STAV

FLIGHT PHASE Landing	**TASK DESCRIPTION** Precision Landing from Vertical Offset
PILOT	**DATE**
RUN NUMBER	
CHR	

FIXED PARAMETERS

Wind: 15 knots crosswind Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 4 NM out Initial Speed: 200 knots Initial Heading: On LOC ALT: 1000 ft AGL Landing Speed: V_{app}-10	Long Offset: + 50 ft vertical Offset from G/S (0.5 dot above) Cloud Breakout: 300 ft AGL GW: 232683 lb for STAV CG pos: Same as 1

VARIED PARAMETERS

Approach Airspeed:	175	195			
Control System:			Alpha	Gamma	Pitch Rate

EVALUATION SEGMENT
Precision Landing from Vertical Offset

Start Evaluation: 600 ft AGL, Approach speed, Descending
End Evaluation: Simulated Touchdown

EVALUATION BASIS
Evaluate handling qualities when landing in a high-gain task. There should be no tendency to bobble in pitch or roll for PIOs.

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Aim Point	50 x 500	100 x 1000
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Deviation from Land A/S @ Touchdown (KEAS)	0	+/ - 5	+/ - 10
Maximum Touchdown Sink Rate (ft/ sec)	<4	4	6
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. At “cloud breakout”, visually correct glideslope to make touchdown at target. Maintain desired vertical velocity and approach speed.
3. Continue to fly final approach until flare.
4. Touchdown target is designated on runway.

FEEL SYSTEM

Baseline

Aft Stick Gain = ____________

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record task and performance parameters at simulated touchdown.

PILOT TECHNIQUE

Baseline

Spoilers in at _______ AGL

UNCLASSIFIED

Figure C-9 – LAMARS Test Card 6

Flight Test Cards

The following test cards were used during flight testing on the Total In-Flight Simulator (TIFS) aircraft.

TASK ID **TASK**

TIFS-1 CALM **Precision Landing**

UNCLASSIFIED

HAVE STAV

FLIGHT PHASE	TASK DESCRIPTION	PILOT	DATE	RUN NUMBER
Landing	Precision Landing from Normal 2.5 deg Approach			

FIXED PARAMETERS

Wind: Calm Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 5 NM out Initial Speed: 185 knots Initial Heading: On LOC ALT: 1000 ft AGL	GW: 232683 lb for STAV CG pos FS: 1044.14 in BL: -0.04 in WL: 107.27

VARIED PARAMETERS

Pilot:	1	2	3		
Control / Feel System:				Baseline	Secondary

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. Continue to fly final approach until flare.
3. Touchdown target is designated on runway.

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record task and performance parameters at simulated touchdown.

EVALUATION SEGMENT

Precision Landing from Normal approach

CHR

Start Evaluation: 600 ft AGL, Approach speed, Descending
End Evaluation: Simulated Touchdown

EVALUATION BASIS

Evaluate handling qualities when landing in a high-gain task. There should be no tendency to bobble in pitch or roll for PIOs.

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Lateral Aim	+/- 25	+/- 50
	Long Aim	+1000/-500	+1500/-750
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Maximum Touchdown Sink Rate (ft/ sec)	<4	4	6
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

FEEL SYSTEM

Baseline

Long Force Gradient = 5 x Baseline – start at 100 ft above touchdown level

PILOT TECHNIQUE

Baseline

Spoilers in at 30 ft above touchdown level

UNCLASSIFIED

Figure C-10 – TIFS Test Card 1

TASK ID **TASK**

TIFS-1 XW **Precision Landing**

UNCLASSIFIED

HAVE STAV

FLIGHT PHASE	TASK DESCRIPTION	PILOT	DATE	RUN NUMBER
Landing	Precision Landing from Normal 2.5 deg Approach			

FIXED PARAMETERS

Wind: 15 knots crosswind Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 5 NM out Initial Speed: 185 knots Initial Heading: On LOC ALT: 1000 ft AGL	GW: 232683 lb for STAV CG pos FS: 1044.14 in BL: -0.04 in WL: 107.27

VARIED PARAMETERS

Pilot:	1	2	3		
Control / Feel System:				Baseline	Secondary

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. Continue to fly final approach until flare.
3. Touchdown target is designated on runway.

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record task and performance parameters at simulated touchdown.

EVALUATION SEGMENT

Precision Landing from Normal approach

CHR

Start Evaluation: 600 ft AGL, Approach speed, Descending
End Evaluation: Simulated Touchdown

EVALUATION BASIS

Evaluate handling qualities when landing in a high-gain task. There should be no tendency to bobble in pitch or roll for PIOs.

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Lateral Aim	+/- 25	+/- 50
	Long Aim	+1000/-500	+1500/-750
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Maximum Touchdown Sink Rate (ft/ sec)	<4	4	6
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

FEEL SYSTEM

Baseline

Long Force Gradient = 5 x Baseline – start at 100 ft above touchdown level

PILOT TECHNIQUE

Baseline

Spoilers in at 30 ft above touchdown level

UNCLASSIFIED

Figure C-11 – TIFS Test Card 2

TASK ID **TASK**

TIFS-2 CALM **Lateral Offset Landing**

UNCLASSIFIED

HAVE STAV

FLIGHT PHASE Landing	**TASK DESCRIPTION** Precision Landing from Lateral Offset 2.5 deg Approach		**PILOT**	**DATE**	**RUN NUMBER**
FIXED PARAMETERS			**EVALUATION SEGMENT** Precision Landing from Lateral Offset		**CHR**
Wind: Calm Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 5 NM out Initial Speed: 185 knots Initial Heading: On LOC ALT: 1000 ft AGL	Lat Offset: +/- 200 ft offset from LOC Cloud Breakout: 300 ft AGL GW: 232683 lb for STAV CG pos: Same as 1	Start Evaluation: 600 ft AGL, Approach speed, Descending End Evaluation: Simulated Touchdown		

EVALUATION BASIS

Evaluate handling qualities when landing in a high-gain task. There should be no tendency to bobble in pitch or roll for PIOs.

VARIED PARAMETERS

Pilot:	1	2	3		
Control / Feel System:				Baseline	Secondary

PERFORMANCE STANDARDS

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Lateral Aim	+/- 25	+/- 50
	Long Aim	+1000/-500	+1500/-750
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Maximum Touchdown Sink Rate (ft/ sec)	<4	4	6
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. At "cloud breakout", visually correct course to recapture runway centerline.
3. Continue to fly final approach until flare.
4. Touchdown target is designated on runway.

FEEL SYSTEM

Baseline

Long Force Gradient = 5 x Baseline – start at 100 ft above touchdown level

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record task and performance parameters at simulated touchdown.

PILOT TECHNIQUE

Baseline

Spoilers in at 30 ft above touchdown level

UNCLASSIFIED

Figure C-12 – TIFS Test Card 3

TASK ID	TASK		
TIFS-2 XW	Lateral Offset Landing	UNCLASSIFIED	HAVE STAV

FLIGHT PHASE	TASK DESCRIPTION	PILOT	DATE	RUN NUMBER
Landing	Precision Landing from Lateral Offset 2.5 deg Approach			

FIXED PARAMETERS

Wind: 15 knots crosswind Config: Gear down, 30 deg spoiler bias, mid-fuel weight with payload RWY surface: Concrete	Initial Position: 5 NM out Initial Speed: 185 knots Initial Heading: On LOC ALT: 1000 ft AGL	Lat Offset: +/- 200 ft offset from LOC Cloud Breakout: 300 ft AGL GW: 232683 lb for STAV CG pos: Same as 1

VARIED PARAMETERS

Pilot:	1	2	3		
Control / Feel System:				Baseline	Secondary

TEST PROCEDURE

PILOT

1. Perform normal approach and landing attitude corrections.
2. At “cloud breakout”, visually correct course to recapture runway centerline.
3. Continue to fly final approach until flare.
4. Touchdown target is designated on runway.

TEST ENGINEER/PILOT NOT FLYING

Record pilot comments and CHR for each run.

Record task and performance parameters at simulated touchdown.

EVALUATION SEGMENT — **CHR**

Precision Landing from Lateral Offset

Start Evaluation: 600 ft AGL, Approach speed, Descending
End Evaluation: Simulated Touchdown

EVALUATION BASIS

Evaluate handling qualities when landing in a high-gain task. There should be no tendency to bobble in pitch or roll for PIOs.

PERFORMANCE STANDARDS	TARGET	DESIRED	ADEQUATE
Landing Zone (for ref. point btwn main gear) (ft)	Lateral Aim	+/- 25	+/- 50
	Long Aim	+1000/-500	+1500/-750
Maximum Bank Angle Below 50 ft AGL (deg)	0	+/ - 5	+/ - 7
Maximum Touchdown Sink Rate (ft/ sec)	<4	4	6
Deviation from RWY heading @ Touchdown (deg)	0	+/ - 2	+/ - 4

FEEL SYSTEM

Baseline

Long Force Gradient = 5 x Baseline – start at 100 ft above touchdown level

PILOT TECHNIQUE

Baseline

Spoilers in at 30 ft above touchdown level

UNCLASSIFIED

Figure C-13 – TIFS Test Card 4

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Appendix D – TIFS Flight Test Matrix

Following the simulator testing in the Large Amplitude Multimode Aerospace Simulator (LAMARS), the conditions that warranted further evaluation were selected for flight testing in the Total In-Flight Simulator (TIFS). The matrix below shows the actual flight test runs.

Table D-1 – TIFS Flight Test Matrix

Key of Abbreviations in Modeling and Simulation Matrix			
Pilot		**Task**	
1	Speares	N	Normal
2	Domsalla	L	Lateral Offset
3	Quashnock	(P)	Practice
Feel System		**Feel System**	
B	Baseline	O	LAMARS Optimized

Hour #	Pilot	Required to Meet Objective	Control Type	Feel System	Approach Airspeed	Task	Crosswind
1-1	1	1,2 and 3	Alpha	B	185 KIAS	N(P)	0
1-2	1	1,2 and 3	Alpha	B	185 KIAS	N	0
1-3	1	1,2 and 3	Alpha	B	185 KIAS	N	7
1-4	1	1,2 and 3	Alpha	B	185 KIAS	L(P)	0
1-5	1	1,2 and 3	Alpha	B	185 KIAS	L	0
2-1	1	1,2 and 3	Alpha	B	185 KIAS	L	7
2-2	1	2 and 3	Alpha	O	185 KIAS	N(P)	0
2-3	1	2 and 3	Alpha	O	185 KIAS	N	0
2-4	1	2 and 3	Alpha	O	185 KIAS	N	7
2-5	1	2 and 3	Alpha	O	185 KIAS	L(P)	0
2-6	1	2 and 3	Alpha	O	185 KIAS	L	0
2-7	1	2 and 3	Alpha	O	185 KIAS	L	7
2-8	1	2 and 3	Alpha	O	185 KIAS	N	7
3-1	2	1,2 and 3	Alpha	B	185 KIAS	N(P)	0
3-2	2	1,2 and 3	Alpha	B	185 KIAS	N	0
3-3	2	1,2 and 3	Alpha	B	185 KIAS	N	7
3-4	2	1,2 and 3	Alpha	B	185 KIAS	L(P)	0
3-5	2	1,2 and 3	Alpha	B	185 KIAS	L	0
4-1	2	2 and 3	Alpha	O	185 KIAS	N(P)	0
4-2	2	2 and 3	Alpha	O	185 KIAS	N	0
4-3	2	2 and 3	Alpha	O	185 KIAS	N	7
4-4	2	2 and 3	Alpha	O	185 KIAS	L(P)	0
4-5	2	2 and 3	Alpha	O	185 KIAS	L	0
4-6	2	2 and 3	Alpha	O	185 KIAS	L	7
4-7	2	1,2 and 3	Alpha	B	185 KIAS	L	7
5-1	3	1,2 and 3	Alpha	B	185 KIAS	N(P)	0
5-2	3	1,2 and 3	Alpha	B	185 KIAS	N	0
5-3	3	1,2 and 3	Alpha	B	185 KIAS	N	7
5-4	3	1,2 and 3	Alpha	B	185 KIAS	L(P)	0
5-5	3	1,2 and 3	Alpha	B	185 KIAS	L	0
5-6	3	1,2 and 3	Alpha	B	185 KIAS	L	7

Table D-1 – TIFS Flight Test Matrix (Continued)

Hour #	Pilot	Required to Meet Objective	Control Type	Feel System	Approach Airspeed	Task	Crosswind
6-1	3	2 and 3	Alpha	O	185 KIAS	N(P)	0
6-2	3	2 and 3	Alpha	O	185 KIAS	N	0
6-3	3	2 and 3	Alpha	O	185 KIAS	N	7
6-4	3	2 and 3	Alpha	O	185 KIAS	L(P)	0
6-5	3	2 and 3	Alpha	O	185 KIAS	L	0
6-6	3	2 and 3	Alpha	O	185 KIAS	L	7
6-7	3	N/A	Alpha	B	185 KIAS	N	0
7-1	3	N/A	Alpha	B	185 KIAS	N	0
7-2	1	N/A	Alpha	B	185 KIAS	N	0
7-3	1	N/A	Alpha	B	185 KIAS	N	0
7-4	1	N/A	Alpha	O	185 KIAS	N	0
7-5	1	N/A	Alpha	O	185 KIAS	N	0
7-6	1	N/A	Alpha	B	185 KIAS	N	0
7-7	1	N/A	Alpha	B	185 KIAS	N	0
7-8	1	N/A	Alpha	O	185 KIAS	N	0
8-1	2	N/A	Alpha	B	185 KIAS	N	0
8-2	2	N/A	Alpha	B	185 KIAS	N	0
8-3	2	N/A	Alpha	O	185 KIAS	N	0
8-4	2	N/A	Alpha	O	185 KIAS	N	0
8-5	2	N/A	Alpha	B	185 KIAS	N	0
8-6	2	N/A	Alpha	B	185 KIAS	N	0
8-7	2	N/A	Alpha	O	185 KIAS	N	0
8-8	2	N/A	Alpha	O	185 KIAS	N	0
8-9	2	N/A	Alpha	O	185 KIAS	N	0
9-1	3	N/A	Alpha	O	185 KIAS	N	0
9-2	3	N/A	Alpha	O	185 KIAS	N	0
9-3	3	N/A	Alpha	B	185 KIAS	N	0
9-4	3	N/A	Alpha	B	185 KIAS	N	0
9-5	3	N/A	Alpha	O	185 KIAS	N	0
9-6	3	N/A	Alpha	O	185 KIAS	N	0
9-7	3	N/A	Alpha	O	185 KIAS	N	0
9-8	3	N/A	Alpha	B	185 KIAS	N	0
9-9	3	N/A	Alpha	O	185 KIAS	N	0
10-1	1	N/A	Alpha	B	185 KIAS	N	0
10-2	1	N/A	Alpha	B	185 KIAS	N	0
10-3	1	N/A	Alpha	O	185 KIAS	N	0

Appendix E – Additional TIFS Flight Test Results

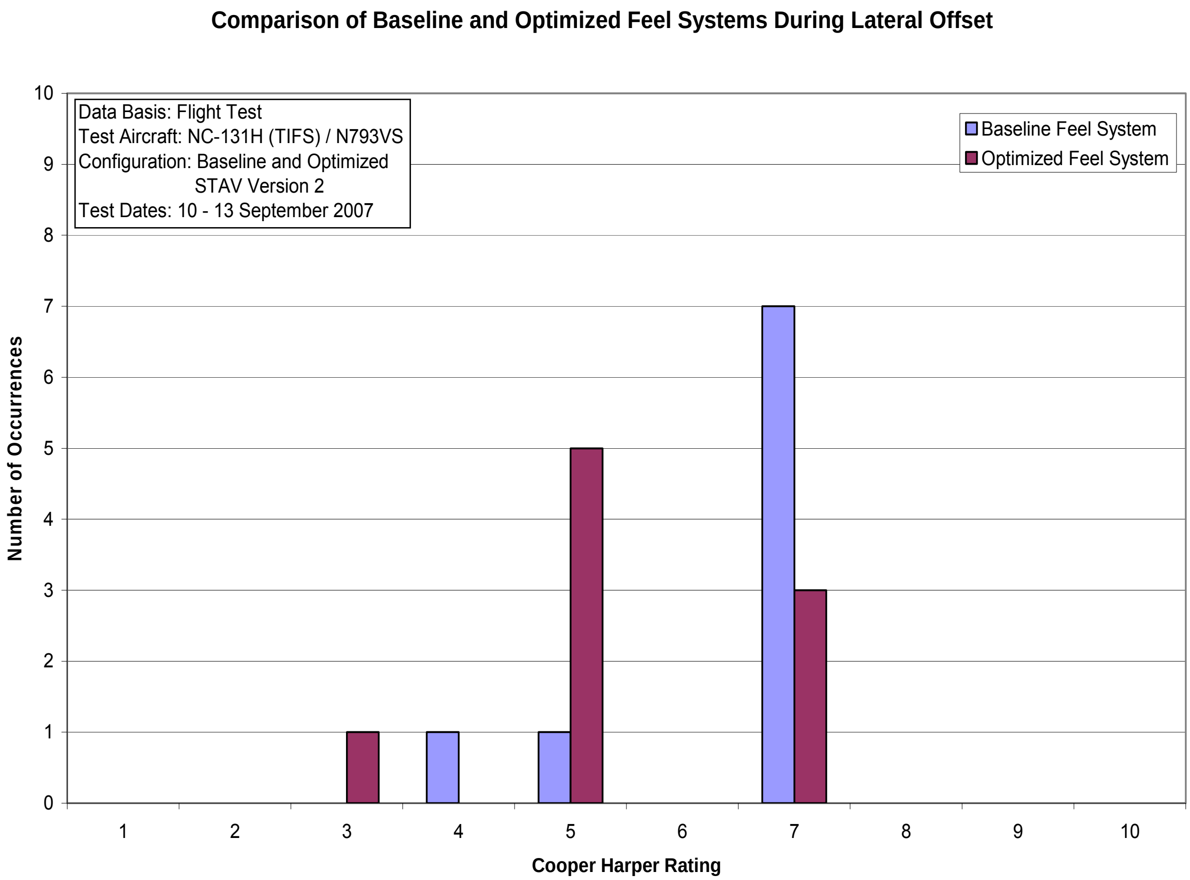

Figure E-1 – Comparison of Baseline and Optimized Systems during Lateral Offset

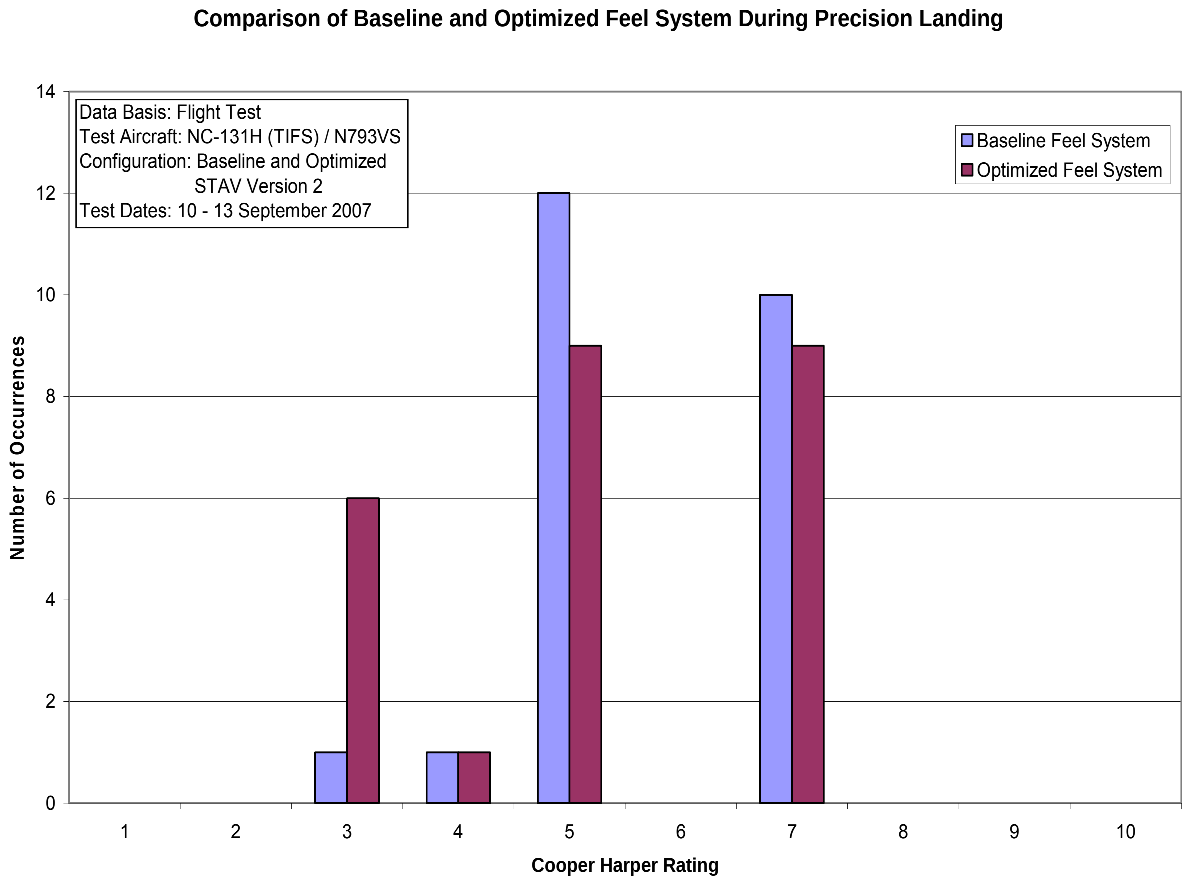

Figure E-2 – Comparison of Baseline and Optimized Systems during Precision Landing

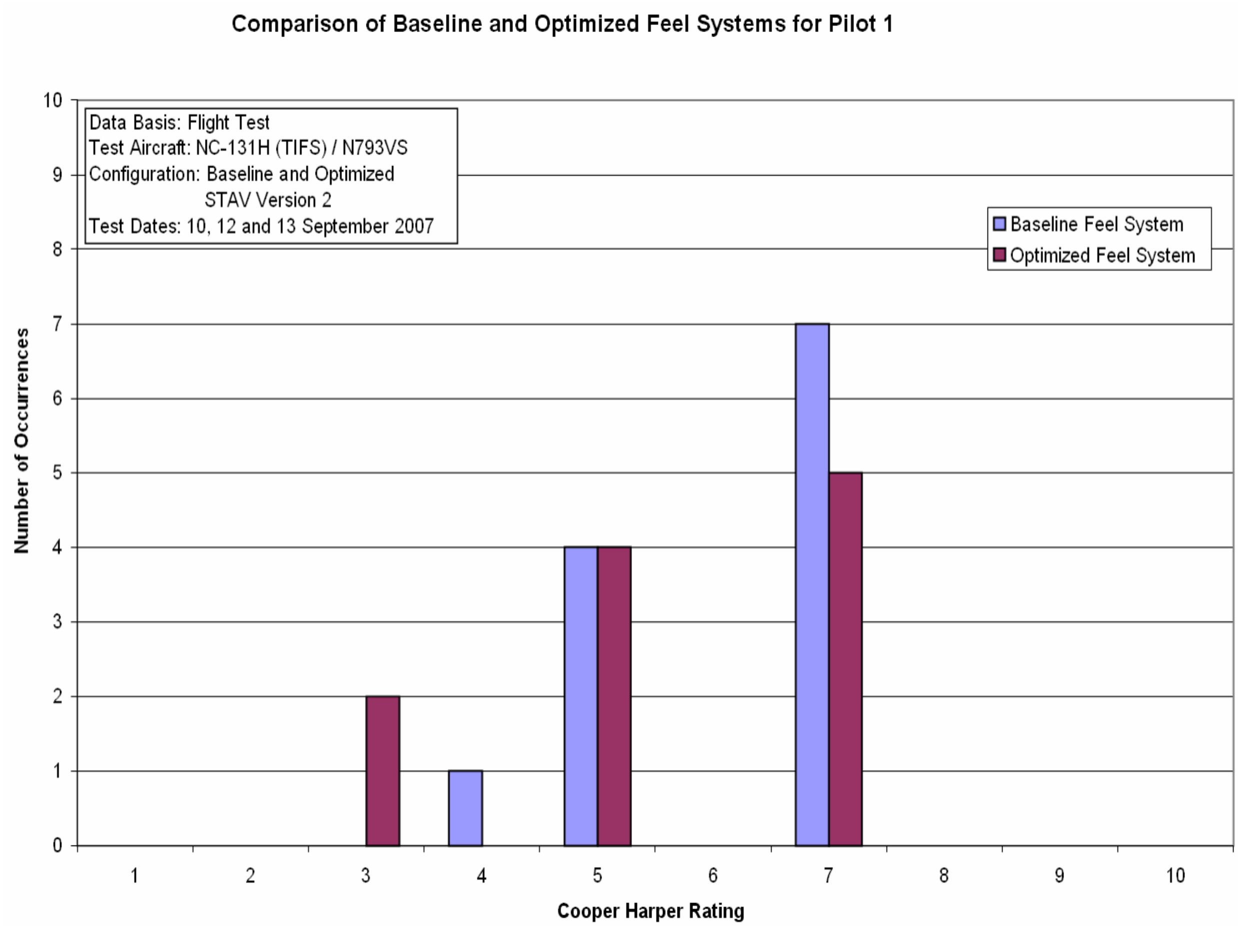

Figure E-3 – Comparison of Baseline and Optimized Systems for Pilot 1

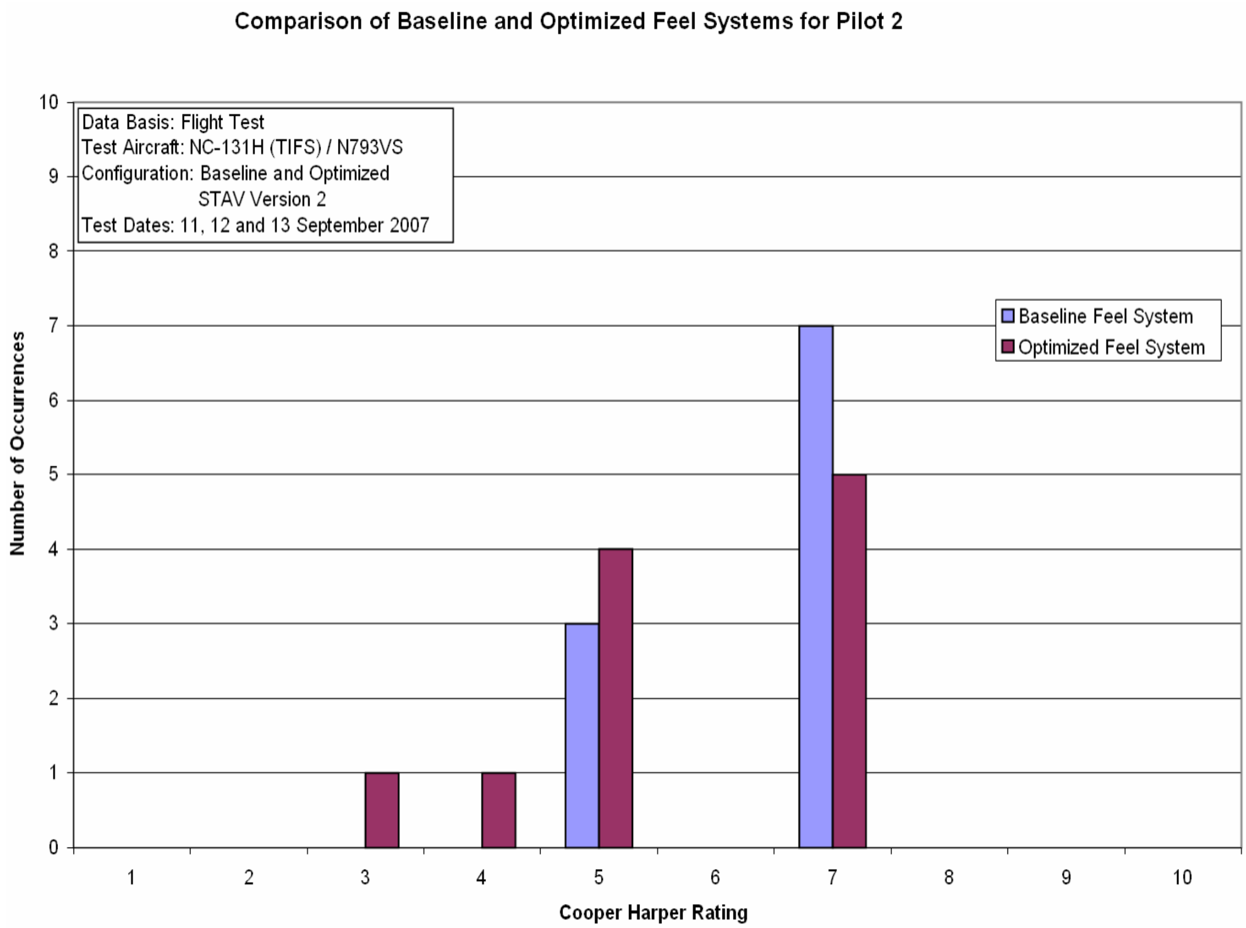

Figure E-4 – Comparison of Baseline and Optimized Systems for Pilot 2

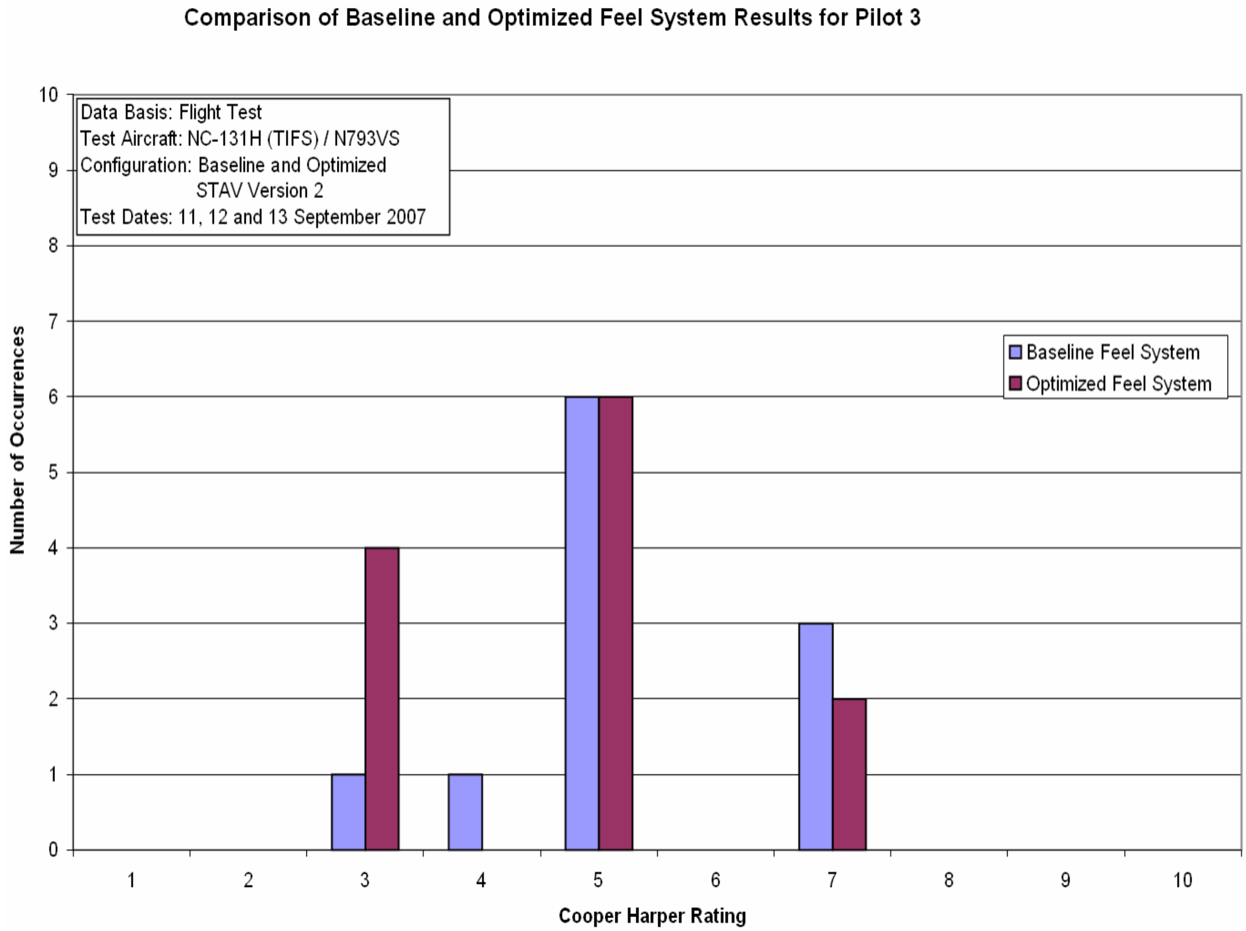

Figure E-5 – Comparison of Baseline and Optimized Systems for Pilot 3

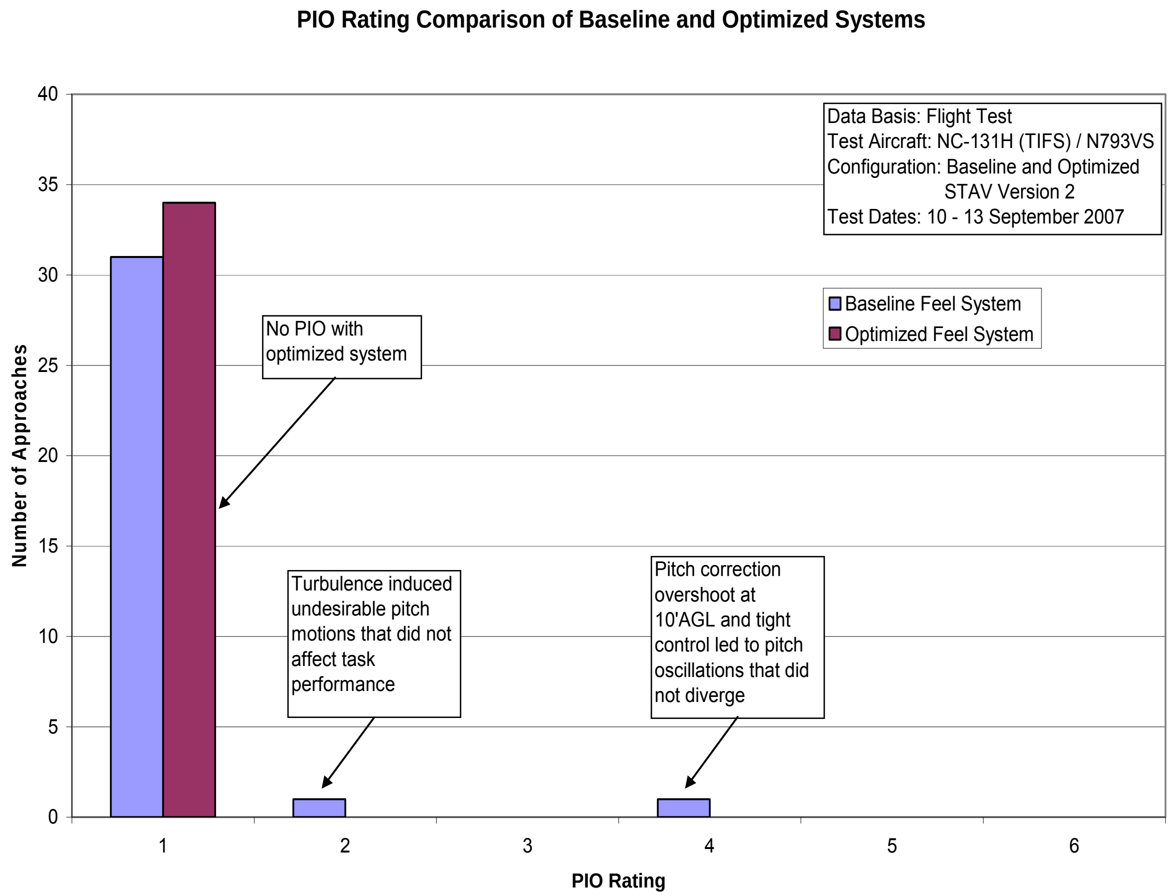

Figure E-6 – PIO Rating Comparison of Baseline and Optimized Systems

Table E-1 – Inadequate Landing Details for Baseline and Optimized Systems

17 Baseline Landings with Inadequate Results						
Flight #	**Record #**	**Reasons for Inadequate Results**	**Length**	**ROD**	**Pitch**	**A/S**
1	6	ROD: 8.1; A/S: 158		X		X
1	16	ROD: 6.2		X		
1	19	Length: 1636	X			
2	8	Pitch: 15.7; A/S: 147			X	X
2	11	Pitch: 15.8; A/S: 138			X	X
2	14	ROD: 9.8; Pitch 15.2; A/S: 134		X	X	X
2	20	Length: 1599; ROD: 8.4; A/S: 137	X	X		X
3	22	Length: 1728	X			
3	23	ROD: 8.6; Pitch: 15.4; A/S: 160		X	X	X
3	26	Pitch: 15.0; A/S: 162			X	X
3	27	Pitch: 18.1			X	
4	21	ROD: 7.7		X		
4	39	ROD: 9.5		X		
4	42	ROD: 9.0		X		
4	43	ROD: 6.4		X		
5	5	ROD:6.3		X		
6	5	Length: 2529	X			
Total			4	10	6	7
12 Optimized Landings with Inadequate Results						
Flight #	**Record #**	**Reasons for Inadequate Results**	**Length**	**ROD**	**Pitch**	**A/S**
1	26	Length: 2101	X			
1	28	ROD: 8.9		X		
1	31	ROD: 6.5		X		
3	5	Length: 2197; A/S: 163	X			X
3	8	Length: 2343	X			
3	11	ROD: 10.9		X		
3	20	Length: 1622	X			
4	21	ROD: 7.7		X		
4	40	Length: 2104	X			
4	44	ROD: 6.8		X		
5	17	Length: 2079	X			
5	25	ROD: 7.1		X		
Total			6	6	0	1

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Appendix F – Lessons Learned

Throughout the course of this thesis, there were several lessons learned that should be highlighted. Most of these lessons learned are specific to an Air Force Institute of Technology-Test Pilot School (AFIT-TPS) thesis, as they were garnered during the execution of a TPS Test Management Project (TMP). However, the general ideas governing test planning and execution can be applied to any research that involves testing, and it is left to the reader to apply these ideas to future projects.

When attempting to define a subject to conduct thesis research on, an AFIT student should use all of the local resources available to find a topic of interest. This not only includes AFIT instructors and advisors, but also extends to other facilities on base. AFIT should continue to improve and expand its relationship with the Air Force Research Laboratory. There are a myriad of topics available for research at this facility, but it remains a relatively untapped resource for the majority of the AFIT student population. In addition to the current thesis symposium where instructors brief students on their topics of interest, AFIT should invite other facilities on base to brief the students on areas of potential research. Although this research may initially require an AFIT advisor to participate in a field they have not been involved in before, it would provide an excellent opportunity to broaden one's overall engineering experience.

Test management projects that can potentially be accomplished off-station should be run through a costs and benefits analysis to determine if the decision to conduct the TMP while at an off-base facility makes sense, from both a technical and risk standpoint. Conducting the TMP flight testing away from Edwards carries significant risk, in the fact that the schedule is constrained by TPS scheduling requirements. The maximum

realistic time away is one five-day work week. When possible, the weekends should be used to travel to minimize the impact on the TPS schedule and to acclimatize the test team to the new conditions, especially if there is a significant time change involved. The flight test schedule is put at risk by both weather and maintenance factors, which could effectively prevent or at best severely limit the number of flight test sorties accomplished. However, the benefits of having contractor facilities, personnel, and equipment on site minimizes some of the maintenance risk, while scheduling the testing according to predicted weather patterns can reduce the weather risk. Try to front-load the schedule as much as possible to allow for any potential flight test delays. This may entail early morning take-offs and triple turns, but the test team must be flexible. If the testing is going to involve traffic pattern work, then testing at an offsite location with minimal traffic can increase the amount of data collected and minimize the impact of air traffic control. The test team can also focus all of their efforts on the project, and not worry about other TPS syllabus events.

When possible, simulations of the flight testing should be accomplished prior to the actual flight testing. This forces the test team to create test cards and run them, so that any mistakes can be worked out prior to wasting flight test time. It also allows the test team to practice the cadence of the testing itself, so that all evaluator pilot and test conductor duties are clearly understood before testing begins. Testing in a simulator allows the test team to create data analysis and reduction tools, something that can streamline the actual flight data reduction. This is particularly valuable when testing on a tight schedule, because a quick-look at the data can allow small modifications to be made to the testing, something that could not be accomplished if all data reduction was saved

until after flight test. Finally, it is imperative that the test team integrate with the simulator technicians early in the test process. A team of technicians that is intimately familiar with the test program provides better adaptability when test procedures must be altered or simulator problems arise. The Air Force Research Laboratory Large Amplitude Multimode Aerospace Research Simulator (LAMARS) technicians provided exemplary support throughout the project, and provide a fantastic example of properly conducted simulator testing.

When conducting tests, the test team must always remember who retains test control. The test team must reference the test plan, especially when testing is not proceeding as planned or when actual results do not match predictions. This will help to prevent the test objectives from evolving during testing.

Contracting issues should be accomplished as early in the TMP process as possible. When dealing with multiple contractors, it can be very easy to lose the scope of the testing and become bogged down in the paperwork. Contracts should be provided to and reviewed by the test team, to ensure that no important factors are omitted (i.e. who pays for the fuel).

Whenever possible, try to have the contractors attend the test plan working group and technical review board in person. It is much easier to discuss technical procedures face to face than it is via a teleconference. The risk of a miscommunication in testing procedure or capability is much higher when conducting all meetings remotely.

Finally, the test team must take model limitations into account during testing, and must be flexible in their test design to account for unforeseen changes in the model. Current Supersonic Tailless Air Vehicle (STAV) model predictions were based on a

constant center of gravity location and aircraft configuration, and testing was designed to take this into account. The instantaneous center of rotation was initially thought to be in front of the actual aircraft, and the test team expected the pilots to feel a motion that was opposite the initial inceptor input. However, the pilots did not perceive this motion during simulator testing. After this simulator testing was conducted, it was discovered that the previous location for instantaneous center of rotation was incorrect. The correct instantaneous center of rotation was nearly collocated with the cockpit, and explained the motions perceived by the pilots. The design of the test plan and objectives minimized the impact of this change, and allowed the team to proceed with flight testing without altering the test plan.

Appendix G – Pilot Pool Information

Table G-1 – ICS Pilot Information

Pilot	Service	Aircraft	Flight Time	Test Experience
1	USMC	F/A-18C	1200	N
2	USN	P-3C	2500	N
3	USAF	B-1B	1350	N
4	USAF	F-16	1300	N
5	USAF	F-15/F-117	2100	Y
6	USAF	B-1/B-2	1400	N
7	USN	P-3C	1500	N
8	USAF	F-16/F-117	2200	N
9	USAF	F-15E	1500	N
10	USAF	F-15C	1300	N
11	USAF	C-130	2900	N
12	USAF	F-15C	1800	Y
13	USAF	F-15E	2100	Y
14	USAF	F-15E	850	N
15	USN	EA-6B	900	N
16	USN	SH-60B	950	N
17	Civilian	Civil	2000	N
18	USN	P-3C	1000	N
19	USAF	F-15E	1065	N

Table G-2 – LAMARS Pilot Information

Pilot	Service	Aircraft	Flight Time	Test Experience
1	USAF	F-15E	1200	Y
2	USAF	A-10	1200	Y
3	USAF	C-9/ C-17	2500	Y
4	USAF	F-15/ F-117	3000	Y

Table G-3 – TIFS Pilot Information

Pilot	Service	Aircraft	Flight Time	Test Experience
1	USAF	F-15E	1200	Y
2	USAF	A-10	1200	Y
3	USAF	C-9/ C-17	2500	Y
4	USAF	F-15/ F-117	3000	Y

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1. REPORT DATE March 2008		**2. REPORT TYPE** Master's Thesis				**3. DATES COVERED** *(From – To)* August 2005 to March 2008
4. TITLE AND SUBTITLE Handling Qualities Evaluation of a Supersonic Tailless Air Vehicle						**5a. CONTRACT NUMBER**
6. AUTHOR(S) Speares, Steven W., Captain, USAF						**5b. GRANT NUMBER**
						5c. PROGRAM ELEMENT NUMBER
						5d. PROJECT NUMBER
						5e. TASK NUMBER
						5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology Graduate School of Engineering and Management Department of Aeronautics and Astronautics (AFIT/ ENY) 2950 Hobson Way Wright Patterson AFB, OH 45433-7765						**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT/GAE/ENY/08-M25
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) USAF Test Pilot School, ATTN: Mr. Gary Aldrich, 220 South Wolfe Ave. Bldg 1220, Edwards AFB CA 93524-6485 AFRL/RBC, ATTN: Mr. Howard Emsley, 2130 Eighth St. WPAFB, OH 45433						**10. SPONSOR/MONITOR'S ACRONYM(S)** USAF TPS
						11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.						
13. SUPPLEMENTARY NOTES CA: Air Force Flight Test Center, Edwards AFB CA CC: 012100						
14. ABSTRACT This thesis presents the results of a handling qualities evaluation of a supersonic tailless air vehicle. The 2006 Quadrennial Defense Review mandated the need for the next generation of long-range strike aircraft by 2018. Due to speed and stealth requirements, this resulted in a tailless aircraft with an instantaneous center of rotation located well forward of that of a conventional aircraft. This thesis examines how this center of rotation affected pilot handling qualities ratings. This effect should have been the most pronounced during approach and landing, and was where the testing focused. The goal of this research was to develop a systematic procedure for evaluating the handling qualities of this aircraft, and to determine how different pilot flying techniques or pilot-inceptor interactions influenced them. This procedure was demonstrated in simulator testing and in flight testing on the Calspan-operated Total In-Flight Simulator aircraft.						
15. SUBJECT TERMS Instantaneous Center of Rotation, LAMARS (Large Amplitude Multimode Aerospace Simulator), Long-Range Strike Aircraft, STAV (Supersonic Tailless Air Vehicle), TIFS (Total In-Flight Simulator), Approach, Landing, VSS (Variable Stability System), Handling Qualities, Flight Testing						
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**		**19a. NAME OF RESPONSIBLE PERSON** Major Paul A. Blue
a. REPORT UNCLASSIFIED	**b. ABSTRACT** UNCLASSIFIED	**c. THIS PAGE** UNCLASSIFIED	SAME AS REPORT	209		**19b. TELEPHONE NUMBER** *(include area code)* (937) 255-3636 x 4714

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18